SCHOOL OF
CIVIL ENGINEERING

INDIANA

DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-82/12

PREDICTION OF SOIL EQUILIBRIUM WATER
CONTENT AND MINEROLOGY EFFECT ON
PERMEABILITY USING PORE SIZE
DISTRIBUTION

S. Prapaharan

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

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Interim Report

PREDICTION OF SOIL EQUILIBRIUM WATER CONTENT AND
MINEROLOGY EFFECT ON PERMEABILITY USING PORE
SIZE DISTRIBUTION

TO: H. L. Michael, Director
Joint Highway Research Project

FROM: A. G. Altschaeffl, Research Engineer
Joint Highway Research Project

July 13, 1982

File: 6-6-14

Project: C-36-5N

The attached Interim Report is the last such report on the HPR Part II Study titled "The Effect of Pore Size Distribution on Permeability and Frost Susceptibility of Selected Subgrade Materials". The Report is titled "Prediction of Soil Equilibrium Water Content and Mineralogy Effect on Permeability Using Pore Size Distribution" and has been authored by S. Prapaharan under the direction of Professor A. G. Altschaeffl.

This is the last Interim Report on this research. Its content is well summarized by the title of the Report. The prediction techniques created in the research are much more rapid than time consuming physical measurements often now utilized. The effect of soil mineralogy on permeability was also investigated and some conclusions reached.

The Final Report on this Study is also in preparation and will correlate and summarize the many findings of the several interim reports toward achievement of the objectives of the research.

This report is submitted as partial fulfillment of these objectives.

Sincerely,

A. G. Altschaeffl/ALM

A. G. Altschaeffl
Research Engineer

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Interim Report

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MINEROLOGY EFFECT ON PERMEABILITY USING PORE
SIZE DISTRIBUTION

by

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Graduate Instructor in Research

Joint Highway Research Project

Project No.: C-36-5N

File No.: 6-6-14

Prepared as a Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana Department of Highways

and the

U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation

Purdue University
West Lafayette, Indiana
July 13, 1982

1. Report No. FHWA/IN/JHRP-82/12	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle PREDICTION OF SOIL EQUILIBRIUM WATER CONTENT AND MINERALOGY EFFECT ON PERMEABILITY USING PORE SIZE DISTRIBUTION		5. Report Date July 13, 1982	
		6. Performing Organization Code	
7. Author(s) S. Prapaharan		8. Performing Organization Report No. JHRP-82-12	
9. Performing Organization Name and Address Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, Indiana 47907		10. Work Unit No.	
		11. Contract or Grant No. HPR-1(20) Part II	
12. Sponsoring Agency Name and Address Indiana Department of Highways State Office Building 100 North Senate Avenue Indianapolis, Indiana 46204		13. Type of Report and Period Covered Interim Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration, from research study entitled, "The Effect of Pore Size Distribution on Permeability and Frost Susceptibility of Selected Subgrade Materials."			
16. Abstract <p>Natural soils and artificial mixtures of silt and kaolin were used. The natural soils were provided by researchers at the University of Illinois; they also provided the associated soil-moisture characteristic curves (as physically measured). Pore size distributions were obtained by mercury-intrusion procedures on freeze-dried specimens.</p> <p>The soil-moisture characteristic curve can be used to predict soil equilibrium water content. This curve relates water content and soil suction. Instead of using the time consuming physical measurement procedures, this study created techniques to predict the curve from pore size distribution data in much less time.</p> <p>The effect of soil mineralogy on permeability is examined by comparing soil permeability to air and to water. Pore size distribution models can predict air permeability or water permeability but not both; this is the mineralogy effect. A correlation was effected between activity and the air to water permeability ratio; this factor is used to correct for the effect and, thus, account for it.</p> <p>Mineralogy effects on clays of low plasticity are relatively small. Predictive equations already created for frost heave rate in such soils require no modifications.</p>			
17. Key Words soil fabric; pore size distribution; air permeability, water permeability; frost heave rate; soil-moisture characteristic curve; equilibrium water content; mineralogic effects		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 171	22. Price

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to his major professor, Dr. A. G. Altschaeffl for his constant support, understanding, and contribution of ideas to the work presented. Special thanks are due Professors R. D. Holtz and L. E. Wood for their valuable counselling and encouragement. Sincere thanks are extended to Dr. D. N. Winslow, Dr. C. H. Juang and Dr. W. L. Dolch for their assistance and helpful discussions.

The author is deeply indebted to Professor B. J. Dempsey of University of Illinois for generously making available to the author the samples and his suction data for use in this study. The laboratory assistance provided by Mrs. Janet Lowell and Mr. M. W. Buis was greatly appreciated.

The financial assistance for this research was provided by the Indiana State Highway Commission and the Federal Highway administration. The research was administered through the Joint Highway Research Project, Purdue University, West Lafayette, Indiana.

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LIST OF ABBREVIATIONS

AASHTO - American Association of State Highway and
Transportation officials

ASCE - American Society of Civil Engineers

ASTM - American Society for Testing Materials

PSD - Pore Size Distribution

HIGHLIGHT SUMMARY

The performance of fine grained soils is influenced by their interaction with water. The permeability and the frost heave rate are among the properties which are affected by the soil-water interaction. In the past, various predictive equations based on volumetric and pore size distribution parameters have been proposed to estimate permeability and frost heave rate. However, these equations did not consider the effect of soil-water interaction. This study investigates this effect by comparing the soil permeability to air and water.

Another concern to engineers is the ability to predict the equilibrium water content beneath pavements. A knowledge of the soil-moisture characteristic curve plays a key role in this prediction. Conventional methods to obtain the soil-moisture characteristic curve involve measurements of soil suction and are time consuming. In this study it was shown that pore-size distribution data can be used to accurately predict the practical soil-moisture characteristic curve in much less time. Thus, prediction of in-place equilibrium water content can now be accomplished on a routine basis.

Natural soils and the artificial mixtures of silt and kaolin were used in this study. The natural soils were compacted by impact compaction whereas the silt-kaolin mixtures were compacted by kneading compaction. The natural soils had been obtained by co-operation of the researchers at the University of Illinois.

The mercury intrusion technique was used to obtain the pore size distribution of the soils. The freeze drying method was used to dehydrate the samples prior to pore size measurements.

A simple falling head air permeability apparatus was used to measure the air permeability of the samples. Water permeability values were taken from the results of Garcia-Bengochea(1978). Soil-moisture characteristic curves obtained by conventional method were provided by Janssen and Dempsey(1980).

The pore size distribution of the soils tested were predominantly bi-modal. However, about one-third of the samples tested exhibited single modal characteristic. Varying the compaction variables produced changes in the position and magnitude of the pore modes, and these variations were reflected in the permeability.

Two permeability models which relate pore size distribution parameters to permeability were examined. These models, with modifications, were successful in

predicting the air permeability, but they failed to predict the water permeability. This is a clear indication that minerology has an influence on permeability. The clay content and composition appear to be the controlling factors. A correlation between the air to water permeability ratio and soil Activity was accomplished to account for the minerologic effect.

It was shown that the minerological effects on clays of low plasticity are very low and hence, the predictive equations developed for frost heave rate in such soils require no modifications.

INTRODUCTION

The performance of fine-grained soils is influenced by their interaction with water. Depending on the boundary conditions and purpose of the project, it may be water flowing that is the concern. At other times it may be how fast the water will freeze. An additional concern is to what equilibrium magnitude will the water content approach, and this will influence the strength and deformation characteristics in service. These questions have been addressed by soil engineers for a long time.

The above matters appear to be different, but, in fact, they are all related to the sizes of the voids within the soils and their continuity. The determination of these sizes of voids has been difficult in the past. As a consequence, empirical predictive equations have been developed based on gross volumetric parameters or grain size distribution, and they have had limited success for sand.

These procedures, however, failed for the fine-grained soils. In recent years, efforts have been made to directly measure the pore size distribution of such soils and relate these to the soil properties. These studies produced suitable prediction procedures for soils of low activity;

therefore, the effect of mineralogy was not considered.

One of the purposes of this project is the examination of the effect of soil mineralogy upon the prediction of water permeability for the soils. Mineralogy has an effect by "bonding" water to the sides of the void spaces (by electro-chemical attraction forces) to change the "effective" pore dimension through which water is moving. In the present study an attempt has been made to shed some light on the effect of mineralogy and fabric on permeability and freezing rate of fine grained soils by comparing their permeability to air and water.

A second objective of the study is to develop a method to predict the equilibrium moisture content beneath pavements. It is known that such equilibria are reached under certain conditions. Existing methods utilize the soil-moisture characteristic curve and the depth to water table to predict the moisture content.

Conventional methods to obtain the soil-moisture characteristic curve involve measurements of soil suction and are time consuming. This study focuses attention on the use of the mercury intrusion technique to obtain the soil-moisture characteristic curve by relating suction to pore size distribution characteristics. This procedure is much quicker, and, once again, recognizes the dependence of this behavior upon the pore sizes which control it.

The mercury intrusion technique was used to obtain the pore size distribution of the soils. The freeze drying method was used to dry the samples before intruding with mercury.

A simple falling head air permeability apparatus was used to measure the air permeability of the soil samples. Water permeability values were taken from the results of Garcia-Bengochea(1978). Soil-moisture characteristic curves obtained by conventional methods were provided by Janssen and Dempsey(1980).

1 - LITERATURE REVIEW AND GENERAL DISCUSSION

1-1 Permeability and Fabric of Finegrained Soils

Permeability is one of the important properties of soils of interest to geotechnical engineers. It influences, among other things, rate of settlement, seepage, dewatering, and drainage.

Permeability of compacted soils is usually measured in the laboratory using the laboratory compacted samples. When these values are used in the analysis of a field problem enormous error may result. The main reason for this is the difficulty in replicating the field soil fabric.

Pore size distribution measurements have been used to predict the permeability and compare the fabric of laboratory and field compacted samples. One of the main objectives of this study is to explore the effect of minerology on permeability by comparing the air and water permeability, and to develop predictive equations for permeability using pore size distribution measurements.

This section discusses the importance of minerology on the flow of water, reviews the results of previous studies concerned with the permeability and fabric of compacted

clays, and examines two permeability prediction models which incorporate pore size distribution parameters.

1-1.1 Effect of Minerology on Permeability

Clay minerals are very small colloidal sized crystalline particles (diameter less than 1 micron), derived primarily from chemical weathering of certain rock forming minerals. The individual crystals look like tiny plates or flakes, and these flakes are found to consist of many crystal sheets which have a repeating atomic structure. Two fundamental crystal sheets, the tetrahedral or silica, and the octahedral or alumina, are found to exist. The particular way in which these sheets are stacked, together with different bonding and different metallic ions in the crystal lattice, constitute the different clay minerals. It is rather common that the cations in the octahedral sheets are substituted by different ions of approximately the same physical size; this process is called isomorphous substitution (Yong and Warkentin, 1975).

Isomorphous substitution and imperfections in the crystal lattice lead to negative electric charges on clay particles. Cations from the pore water are attracted to the particles to maintain electro-neutrality. These ions are called the exchangeable cations and their number is the cation-exchange-capacity or the amount of negative charge per unit weight or per unit surface area of the clay.

Clay particles in soils are always hydrated, i.e. surrounded by layers of water molecules called adsorbed water. The forces holding water molecules to the clay arise from hydrogen bonding, and electro-static attraction. The water molecules are held against the clay mineral surface in many layers and the bonding forces become weaker with distance from the surface. The density and viscosity of this water close to the clay surface is higher than that of free water (Low, 1961, 1979). There is lack of agreement as to the thickness of the hydration layer, and also there is no sharp division between water of hydration and free water in a clay-water system.

In a dry clay, adsorbed cations are tightly held against the surface. When the clay is placed in water, there is a tendency for the adsorbed cations to diffuse away from the clay surface in order to equalize the concentration throughout. Their freedom to do so, however, is restricted by the negative electric field originating in the particle surfaces. The negative surface and the distributed charge in the adjacent phase are together termed the diffuse double layer. The interaction of diffuse ion layers of adjacent particles is given as an explanation for swelling of clays.

The flow of water through clayey soils is affected by the clay-water interaction. High viscosity of water near the clay surface and counterelectro-osmosis are said to affect the permeability. The other factors affecting the

flow of water are discussed in the following section. If high viscosity exists in an appreciable volume of the clay pore space, flow rates will be less than those predicted from Poisuille's law which assumes that the pore liquid viscosity is a constant throughout and equal to the viscosity of free water.

The phenomenon of counterelectro-osmosis can be explained as follows: the movement of water past the clay surface causes a downstream transport of the ionic charges in the diffuse part of the double layer; this displacement develops a streaming potential which causes electro-osmosis in a direction opposite to the forward flow; the net result is a reduction of the flow rate below that predicted from Poisuille's law.

1-1.2 Permeability

The permeability of soils has been of interest to researchers for a long time. Darcy, in 1856, proposed his well known law for flow of fluids through porous media. Kozeny(1927) suggested an equation to predict the coefficient of permeability using the physical characteristics of the porous medium. Carman(1956) modified Kozeny's equation and since then it has been called Kozeny-Carman equation. However this equation did not consider the interaction between the pore fluid and the porous medium.

Several researchers have attempted to measure the permeability of clays to both polar and non-polar fluids. They found that the permeability to polar fluids was very much lower than to non-polar fluids. The applicability of Darcy's law and the Kozeny-Carman equation has also been investigated, and discrepancies were found. Various explanations were offered for these discrepancies, and since these are of importance to the present study they will be discussed in detail below.

Macey(1942) reported rates of flow for benzene 100,000 to 1,000,000 times greater than that for water in his clay. He believed that the most important cause for the lower permeability in water is the anomolous viscocity of the water near the clay surface.

Michaels and Lin(1954, 1955) showed experimentally that the permeability of kaolinite decreased markedly as the polarity of the permeating fluid increased and that the most important factor controlling the permeability of kaolinite was the degree of dispersion of the kaolinite in the presence of polar fluids. They also concluded that electro-osmotic counter flow might be of some importance when aqueous solutions were used as permeants as adsorbed liquid surface films appeared to have little effect on the permeability.

Reeve(1953) measured air and water permeability for various soils. The clay content of the soils he tested varied from 2.3 to 38 percent, and the exchangeable-sodium-percentage ranged between 0 and 75. He found that the air to water permeability ratio varied with exchangeable-sodium-percentage as well as with clay content, and the variations ranged from 1 to 10,000. He attributed these variations to structural instability caused by deflocculation and dispersion. Brooks and Reeve(1959) also obtained similar results. However, these authors did not correct their air permeability values for probable gas slippage which would have resulted in higher values for measured permeability.

Corey(1957) found that the permeability ratio for loamy sand was about 2, even after correcting for gas slippage, and suggested that the ratio might be much higher for clayey soils.

Mesri and Olson(1971) conducted one dimensional consolidation tests on kaolinite, illite, and smectite. They used polar and non-polar fluids as pore fluids, and calculated the coefficients of permeability using Terzaghi's theory of consolidation. Some of their findings are as follows:

- 1) The coefficients of permeability were found to be largest for non-polar fluids, smaller for polar fluids of low dielectric constant, and lowest for water.

- 2) At the same void ratio the kaolinite was shown to be 200,000 times more pervious than smectite to water; illite was 200 times more pervious than smectite.
- 3) The coefficient of permeability to non-polar fluid was the same for all three clays at a given void ratio.

They were of the opinion that the effects of adsorbed water was inadequate to cause these differences, and explained the cause of differences as follows: the clay particles form stable aggregates and the main fluid flow takes place in the large voids between the aggregates; in the presence of polar fluids the aggregates break down and there results a dispersive structure with low permeability; the degree of dispersion depends on the polarity of the pore fluid and the physico-chemical properties of the soil minerals.

The Kozeny-Carman equation has been found to be unsuitable for the prediction of the permeability of fine grained soils by Lambe(1954), Michaels and Lin(1954), and Olsen(1962). Lambe(1954) found that the changes in permeability with water content could not be accounted for by changes in dry density or void ratio, and he concluded that they must have been caused by the changes in the structure of the soil particles, i.e., the soil fabric.

Olsen(1962) measured hydraulic flow rates, electrical conductivities, and streaming potentials for flow through kaolinite, illite, and Boston blue clay. He found discrepancies between measured flow rates and those calculated from Kozeny-Carman equation. He concluded that electro-osmotic counter flow, high viscosities, and tortuous flow paths failed to account for the permeability characteristics he measured, and suggested that unequal pore sizes was the cause for the discrepancies.

Schmid(1957) suggested that an adsorbed layer can be considered as a stationary boundary layer, and derived an equation for permeability using effective porosity.

Non-Darcy flow has been observed by many researchers. Von Engelhardt and Tunn(1955) measured flow rates through clay-bearing sandstones and found that the flow rates increased more rapidly with hydraulic gradient than predicted by Darcy's equation. They interpreted the behavior as resulting from the water behaving as a non-Newtonian liquid whose viscosity depends on the shearing force, and hence, on the gradient. Kemper(1960) postulated that, such effects results from electro-kinetic coupling or electro-osmotic counter flow.

Hansbo(1960) and Martin(1962) suggested that this type of behavior could have resulted from particle movements leading to reversible void plugging and unplugging.

Low(1961) argued that that the existence of a quasi-crystalline adsorbed water structure could explain non-linearity.

Miller and Low(1963) observed a threshold gradient, and suggested that the presence of quasi-crystalline water and unequal pore sizes were the reasons for this behavior. Olsen(1965) suggested that undetected experimental errors could have resulted in the apparant threshold gradient in the published results and favored a particle migration concept. This was also supported by Mitchell and Younger(1967).

Miller et al.(1969) reported that no threshold gradient was found for soils with montmorillonite content of upto 50 percent. Russel et al.(1971) also found no evidence for non-linear flow in non-swelling soil, but they reported non-linear flow in a soil having small content of swelling clay.

The flow of gases through porous media has been investigated by many researchers including Muskat(1946), Sullivan and Hertal(1940), and Klinkenberg(1941). Darcy's law has been found to be applicable at low pressure gradient, and equations were derived for compressible flow. It was noted that, with samples of lower permeability, the values obtained with gases are generally higher than those obtained using liquids.

Adzumi(1937) suggested that slip occurred with gases. Dolch (1956) explained this as follows: "When the mean free path of gas becomes appreciable with respect to the size of the channels through which it is flowing, the viscous-flow assumption of zero gas velocity at the channel wall no longer holds and gas begins to slip past the channel walls. The slip contributes an additional component to the velocity beyond that of viscous flow and this component becomes appreciable at low pressures and/or when the channels are extremely small. Klinkenberg(1941) suggested that the true permeability can be obtained by measuring the apparent permeability as a function of reciprocal mean pressure and determining the intercept of the plot.

Several researchers including Ladd(1960) and Langfelder et al.(1968) measured air permeability of partially saturated kneading compacted clays, and reported that near optimum water content air permeability was essentially zero. Blight(1971) conducted air permeability tests on soils from tailings deposits, which were subsequently compacted and air dried in the laboratory, and found non-linear flow characteristics. Serracin(1980) measured air permeability of compacted grundite and found that Darcy's law was obeyed.

Summarizing, recent investigations suggest that no threshold gradient exists in non-swelling soils, and non-linearity, if found, could have resulted from particle migration. The large difference in permeability to polar

and non-polar fluids is due to the break down of aggregate structure in the presence of polar fluids.

1-1.3 Fabric

The terms fabric and structure of soil, as used in this study, were defined by Yong and Sheeran (1973) as follows:

"The structure of the soil has been defined as that property of soil which provides for its integrity. An important component of structure is its fabric, i.e., the physical arrangement of soil particles including particle spacing and pore size distribution. When soil fabric is considered in conjunction with bonding forces and particle interaction mechanism developed, the structure of soil is obtained".

The fabric can be divided broadly into two categories: macrofabric, and microfabric. Macrofabric can be seen with the naked eyes or a hand lens, and it includes features such as stratification, fissures, voids, and large scale inhomogeneities. Microfabric requires at least an optical microscope to be seen (Mitchell, 1976). Of primary concern to this study of clayey soils is the microfabric, and it is this category of fabric that is discussed in more detail below.

Several conceptual model of the microfabric of natural soils have been proposed in the past, the earliest of which

were conceived by Terzaghi(1925), Goldschmidt(1926), and Casagrande(1932). Terzaghi's model assumes that the individual clay minerals stick to each other at the points of contact with forces sufficiently strong for the creation of a "honeycomb" arrangement. Goldschmidt(1926) suggested that the clay particles in highly sensitive clays were arranged in an unstable card house arrangement. Casagrande(1932) postulated that "honeycomb" arrangements existed in sensitive marine soils and that these were basically similar to Terzaghi's concept; in addition, he also suggested that the particle arrangements located in the smallest gaps between adjacent silt particles were highly compressed whereas those located in the larger spaces between silt particles had undergone relatively little compression. Since then, there have been many other models suggested by various researchers. Collins and McGown(1974) summarized the various models postulated to that time, and suggested a few modifications to some of the earlier concepts.

Lambe presented an explanation of the microstructure of inorganic soil in 1953, and subsequently suggested a model of the structure of compacted clay(1958). He used colloidal and crystal chemistry to postulate his model, and individual particles were his predominant units. The Lambe concept suggested that on the dry side of optimum water content, the moisture deficiency causes the shrinkage of the double

layer, and allows the particles to approach sufficiently close for edge to face attractions to develop; this results in a flocculated structure. On the wet side of optimum water content the fully developed double layers prevent close approach and a face to face arrangement dominates; this is termed a dispersed structure. Seed and Chan(1959) related this concept to observed engineering behavior of clays compacted dry and wet of optimum.

Since then various researchers who could not explain their experimental results using Lambe's model suggested modifications to his model. Olsen(1962) postulated that clay particles may occur in clusters, and these clusters make up the soil structure. It is interesting to note that Carman, in 1959, presented a similar concept for fine grained soils. Mesri and Olson(1971) also suggested a similar model for clays. However, recent studies of soil fabric using transmission and electron microscopy gave strong evidence for the need for modifications to existing models. Sloane and Kell(1966) found no evidence for edge-to-face structure for kaolinite samples compacted on the dry side of optimum, but, rather, found an essentially random arrangement of particles or domains. Smart(1969) defined the term domain and gave a classification of domains and sub-domain structures.

Barden and Sides(1970) observed that there has been a marked difference in structure at low magnifications between

samples compacted dry of optimum and those compacted wet of optimum, but little difference was found at high magnifications. Barden and Sides hypothesized that at low compaction moisture contents, the macropeds have a high strength and are able to resist the compaction pressures without much distortion. Thus, the voids between these macropeds are of the same macroscale and are filled with air. As the compaction moisture content is increased, the macropeds become wetter and consequently weaker. Thus, during compaction, the macropeds are more easily distorted and the size of the interpedal air voids is reduced. Further increase in the compaction moisture content causes the macropeds to become even weaker and during compaction they are distorted to fill the macro pores which tend to disappear. Thus, it is impossible to distinguish the individual macropores and at low magnification the soil appears homogeneous. Independent studies by Hodek(1972) suggested a similar model. Yong and Sheeran(1973) provided a scheme of classification which identifies the various observable fabric units with reference to the mode of fabric viewing.

Although most of the above analysis were strictly qualitative a few researchers attempted to quantify the fabric. Mitchell(1956) used optical microscopy to quantify the orientation of clay particles by using a measure of light transmission through the fabric. The measurement of

pore size distribution of compacted clays remained a neglected subject for a long time. A number of researchers from Purdue University attempted to use pore size distribution as a descriptor of fabric of compacted clays.

Diamond(1970, 1971) used scanning electron microscopy, x-ray diffraction, and pore size distribution methods to study the fabric of impact compacted clays. His electron micrographs of clay samples appeared to be similar to that of Barden and Sides(1970). X-ray diffraction measurements showed no evidence of increased particle orientation with increasing molding water content as suggested by Lambe(1958). Pore size distribution measurements indicated that content of the fine pores (inter particle spaces, 0.02-0.08 μ m) was not affected by the compaction water content. He also suggested that the size of a domain is about 5 μ m.

Sridharan et al. (1971) performed pore size distribution measurements of statically compacted clays. They found that volume changes due to compaction at a given water content was at the expense of larger pores. They further stated that the different clays appear to have characteristically different overall features in their pore size curves and these variations are not simply correlated with differences in the grain size distributions.

Ahmed(1971) found no significant difference in the shapes of pore size distribution curves between clays

prepared by impact and kneading compaction to a common water content and density. Electron micrographs of compacted clay samples obtained by him appeared to be similar to that of Diamond(1971).

Bhasin(1975) observed that increasing the compactive effort on the dry side of optimum for a given soil decreases the total porosity and diminishes the fraction of larger pores. Increasing the compactive effort on wet side of optimum had little effect on either the total porosity or the distribution of pore sizes. Garcia-Bengochea(1978) also stated that the changes in soil fabric was generally at the expense of the larger pores.

The concept of a deformable aggregate model is strongly supported by the above described results.

White(1980) studied the fabric of laboratory and field compacted soils. He concluded that fabric was significantly different for both soils. The differences were found to exist at all water contents except those near the optimum water content. The differences near the optimum water content may have been due to the inability to accurately define that water content, especially for the field relationships. Not only were laboratory and field fabrics different, but also different field equipments create significantly different fabric; however, impact and kneading compaction in laboratory produced fabrics not significantly

different.

1-1.4 Permeability Models

Attempts have been made in the past to correlate permeability with certain measurable properties of the soils such as grain size distribution, porosity, internal surface area, etc. Hazen(1911) proposed an empirical equation based on grain size distribution to predict permeability of sands. Various other empirical equations were also proposed. Since these correlations did not consider the pore geometry they had only limited success. Efforts to refine this approach by introducing empirical grain shape and packing parameters have not won general acceptance. Some researchers attempted to correlate permeability with porosity or void ratio (Jacob,1946, Taylor,1948). However, due to the strong dependence of flow rate upon width, continuity, shape, and tortuosity of the conducting channels, this kind of approach will not yield satisfactory results(Hillel, 1980).

Kozeny-Carman theory, which is based on the concept of hydraulic radius, enjoyed popularity for a long time. However, its applicability to fine grained soils was questioned by various researchers as discussed in Section 1-1.2.

Numerous theoretical models have been introduced to represent the porous media by a set of relationships that

are amenable to mathematical treatment. Such models include capillarie, parallel, serial, and branching models.

Purcell(1949) used a modified capillary model to calculate the permeability of sandstone from pore size distribution measurements. Childs and Collis-George(1950) and Marshall(1958) introduced probability into the capillary model theory to improve the model.

Scheidegger(1974) comprehensively discussed the complex nature of porous media, the limitations of conventional models for predicting permeability, and presented several models.

Garcia-Bengochea(1978) used the capillary models by Purcell(1948) and Marshall(1958), and the hydraulic radius model, with few modifications, to predict the permeability of artificial silty clays. Juang(1981) proposed a new model which he used to predict the permeability of sands and sand-clay mixtures.

The main objective of this present study is to find the effect of minerology on permeability. Thus, it was decided to use the simple capillary models used by Garcia-Bengochea(1978); this also faciliated the use of some of his data for this present study. The hydraulic radius model was not used because of the following reasons:

- 1) Hydraulic radius model assumes uniform pores(Carman, 1959). The fine grained soils used in this study

are shown to have non-uniform pores.

- 2) Garcia-Bengochea found that capillary models give a better correlations than hydraulic radius models.

1-1.4.1 Capillary model. The derivation of this model is given in detail by Garcia-Bengochea(1978), and only some important points will be repeated below,

The porous medium is modeled as a set of parallel cylindrical capillaries of varying pore diameters extending from one end of the porous medium to the other. Each capillary is assumed to have a constant radius throughout its length. The frequency of occurrence of each capillary size is determined from the pore size distribution curve.

The permeability is given by the following equation,

$$k = \frac{\gamma n}{32\mu} \int_0^\infty \delta^2 f(\delta) d\delta \quad (1-1)$$

Where k = permeability

γ = unit weight of fluid

μ = absolute viscosity of the fluid

n = porosity

δ = diameter of the pore

$f(\delta)$ = porosity density function

$$\int_0^\infty f(\delta) d\delta = 1 \quad (1-2)$$

Replacing the permeability, k , by the physical permeability, K , and using the relationship $k = KT/\mu$,

equation(1-1) becomes

$$K = C_g E(d^2)n \quad (1-3)$$

where C_g is a shape factor which is equal to 1/32 for cylindrical pores. Also,

$$E(d^2) = \int_0^\infty \delta^2 f(\delta) d\delta \quad (1-4)$$

There are several shortcomings to these equations, as pointed out by Scheidegger(1974):

- 1) all pores are assumed to go in one direction.
- 2) tortuosity is not considered.
- 3) the shape factor is considered constant for all pore sizes.
- 4) the value of $E(d^2)$ is extremely sensitive to the frequency of the larger pores.
- 5) the model is an over simplification of the porous medium.

1-1.4.2 Modified capillary model(Marshall,1958). Childs et al.(1950) and Marshall(1958) employed another form of capillary model using the pore size distribution to calculate permeability. They considered two unit cross-sections of a porous medium placed together such that the pores from one surface are randomly connected to those of the other surface. Each of the cross-sections contain cylindrical pores of varying diameters. The pore size distributions for the cross-sections are assumed to be identical.

It can be shown that,

$$k = \frac{\tau n^2}{32\mu} \int_0^\infty \int_0^\infty \delta^2 f(\delta_i) f(\delta_j) d\delta_i d\delta_j \quad (1-5)$$

where $k, \tau, n, \mu, f(\delta)$ are as defined above.

δ = smaller of the pore sizes δ_i and δ_j .

Rewriting equation (1-5) in terms of pore diameter and physical permeability:

$$K = C_s \bar{d}^2 n^2 \quad (1-6)$$

where

$$\bar{d}^2 = \int_0^\infty \int_0^\infty \delta^2 f(\delta_i) f(\delta_j) d\delta_i d\delta_j \quad (1-7)$$

In summary, the physical permeability can be described by:

$$K = C_s \text{ PSP} \quad (1-8)$$

where PSP is a pore size parameter, and

C_s is a shape factor.

Table 1 presents a summary of the models discussed.

1-2 Soil-Moisture Properties

Subgrade moisture is an important variable in the design and performance of pavements. The moisture content of soils has been related to California Bearing Ratio (which is a measure of shear strength), the dynamic or resilient modulus (which affects the deflection), and the unsaturated hydraulic conductivity (which controls the flow of water during frost heave). Even though the moisture content of a subgrade is known at compaction, the field moisture content can and will be different after some time in service. It

Table 1 SUMMARY OF PERMEABILITY MODELS USED

1) VARIABLE DIAMETER CAPILLARY MODEL

Equation $K = C_s E(d^2)n$

Pore Size Distribution

Parameter $E(d^2)n = \int_0^\infty \delta^2 f(\delta) d\delta$

2) MARSHAL MODEL

Equation $K = C_s \bar{d}^2 n^2$

Pore Size Distribution

Parameter $\bar{d}^2 = \int_0^\infty \int_0^\infty \bar{\delta}^2 f(\delta_i) f(\delta_j) d\delta_i d\delta_j$

where $\bar{\delta}$ is smaller of the
pore sizes δ_i and δ_j

K = Physical Permeability, L^2

n = porosity

C_s = shape factor

δ_i = pore diameter, L

$f(\delta)$ = porosity density function, $\int_0^\infty f(\delta) d\delta = 1$

would be very useful to have a rational method to predict the long-term moisture distribution beneath pavements. In the following section the concept of matric potential or soil suction, and the soil-moisture characteristic curve is explained; in addition an existing rational method to predict the moisture content is discussed.

1-2.1 Soil-Moisture Potential

Soil water contains energy in both potential and kinetic forms, just as any other bodies in nature. As the water moves very slowly in soil, the kinetic energy component is usually ignored in the study of the soil-water system. The potential energy of the soil water can be subdivided into gravitational potential, pressure potential, osmotic potential, and gas potential. The gravitational and pressure potential are the primary force fields in the soil-water system. The osmotic potential, which results from the presence of solute in the system, and gas potential, which is dependent upon external or internal gas pressure, are considered to have minor influence on the total potential, and are normally ignored.

The total potential can be written as follows:

$$H = Z + h \quad (1-9)$$

where Z = gravitation potential or position head

h = pressure head or matric potential

H = total head

When there is no moisture movement, total head is equal to zero.

Therefore,

$$h = -Z \quad (1-10)$$

The matric potential results from capillary and adsorptive forces developed in the soil matrix. It can be visualized as a suction exerted by the soil to pull water up from the water table. This suction is dependent on the soil pore geometry or soil matrix; thus the term matric potential is used (Hillel, 1980).

The concept of matric potential can be easily understood by an analogy made between the pores in the soil and capillary tubes. Water in a narrow tube will rise above the free water level until an equilibrium condition is reached. The water in the tube forms a meniscus at the air-water interface; the dimensions of the meniscus are related to the size of the tube. The smaller the radius of curvature of the meniscus, the higher the water will rise in a capillary tube. A similar meniscus can form in the water between soil particles. The height of capillary rise can be described by the equation,

$$h = \frac{4 T \cos \theta}{\gamma_d} \quad (1-11)$$

where, h = height of capillary rise

T = surface tension of water

θ = contact angle between the wall of the tube and water.

γ = unit weight of water

d = diameter of the tube

1-2.2 Soil-Moisture Characteristic Curve

A graph showing the relationship between moisture content and suction is called the soil-moisture characteristic curve. Since experience shows that soil suction can take on a large range of values, it is common to plot the logarithm of suction in cm of water against moisture content (Figure 1). Several soil scientists including Keen(1931) and Schofield(1935) used this curve to study some aspects of the soil structure. The nature of the capillary pressures and the role they play in petroleum reservoir behavior have been discussed by Levrett(1941) and others.

Several researchers including Croney(1952) of the British Road Research Laboratory, have used suction-moisture content relationships to predict moisture distribution beneath road and airfield foundations, as well as road performance. Green and Corey(1971) used this relationship to predict unsaturated hydraulic conductivity. Elzeftawy and Dempsey(1977) used soil moisture characteristic data along with measurement of saturated hydraulic conductivities to predict unsaturated hydraulic conductivities for highway

Figure 1 Soil Moisture Characteristic Curve

soils. The overall goal has been to formulate a theory which could reliably predict the moisture movement beneath pavements, because moisture movements affect the strength parameters considerably.

Croney et al.(1951) have described the methods used to determine the soil moisture characteristic curve. These methods consist of the tensiometer, the direct suction method, the pressure plate method, and the centrifuge method. Usually no single method can be used to cover the entire moisture tension range, so several methods may be used in actual practice. Purcell(1949) used mercury porosimeter measurements to predict the suction curve.

The soil-moisture characteristic curve can be obtained by two methods:

- 1) In desorption, by taking an initially saturated sample and applying increasing suction to gradually dry the soil, and
- 2) In sorption, by gradually wetting an initially dry sample.

These two methods usually give two different curves; this is the well known hysteresis effect. According to Hillel(1980), the hysteresis effect is attributed to:

- 1) the geometric non-uniformity of the individual pore, called the "ink bottle" effect.
- 2) the difference in contact angle of the advancing

and receding meniscus.

- 3) entrapped air
- 4) swelling, shrinking or aging phenomena.

The amount of water retained at low values of matric suction(between 0 and 1 bar) depends primarily upon the capillary effect, and hence is strongly affected by the soil structure. On the other hand, water retention in the higher suction range is due increasingly to adsorption and is thus influenced less by the structure and more by the texture and specific surface of the soil material.

1-2.3 Prediction of Soil-Moisture Characteristic Curve

Purcell(1949) suggested a method to get the soil-moisture characteristic curve from mercury intrusion measurements. His method is as follows: In the conventional method to get the soil-moisture characteristic curve water is used as the pore fluid. Since it wets the soil surface(i.e. contact angle is less than 90°), surface forces are induced and these forces draw water into the soil pores. However, removal of water from pores will require external pressure. On the other hand mercury, a non wetting fluid, requires external pressure to intrude the pores. Since the Washburn equation applies to both cases, if the measurements with respect to mercury are known, then the capillary pressures for water can be predicted, provided the surface tension and the contact angle for both fluids are known.

Washburn's equation is

$$P_m = \frac{4 T_m \cos \theta_m}{d} \quad (1-12)$$

where T_m = surface tension of mercury.

P_m = pressure required for mercury.

θ_m = contact angle between mercury and soil.

also,

$$P_w = \frac{4 T_w \cos \theta_w}{d} \quad (1-13)$$

where T_w = surface tension of water

P_w = pressure required for water.

θ_w = contact angle between water and soil.

From equation (1-12) and (1-13),

$$P_w = \frac{T_w \cos \theta_w}{T_m \cos \theta_m} P_m \quad (1-14)$$

The soil-moisture characteristic curve predicted from mercury intrusion measurements is equivalent to the desorption curve. At each intrusion pressure to obtain the corresponding moisture content, the intruded volume of mercury should be subtracted from the total volume of pores.

The primary advantage of this method is that it allows one to obtain the soil-moisture characteristic curve over a wide range of pressures within an hour whereas the conventional method takes weeks and also requires the use of different equipment.

1-2.4 Prediction of In-Situ Equilibrium Water Content

Croney and Coleman(1953) used the matric potential (which they called the pore water pressure) and soil-moisture characteristic curve to predict equilibrium moisture contents below road surfaces, where the ground water table is at shallow depths(i.e. about 20 feet in clay soils).

The principles on which their method is based are as follows:

- 1) The pore water pressure(matric potential) tends to an equilibrium value dependent only on the position of the ground water table.
- 2) There is a relationship between pore water pressure in the soil at a given location and the suction of this soil, where suction is the pore water pressure of a sample.
- 3) There is a relationship between suction and water content(soil moisture characteristic curve).

Equilibrium conditions are as follows:

- a) The subgrade soil is at a constant, uniform temperature above 0° C, and
- b) The subgrade soil cannot imbibe or lose moisture through the pavement or adjacent soil masses.

At equilibrium the pore water pressure or matric potential can be expressed by the following equation

$$u = -Z \quad (1-15)$$

where u is the pore water pressure expressed in cm of water and Z is the height above the ground water table. Suction is taken to be the value of pore water pressure of an undisturbed sample which, owing to its removal, has been relieved from all external stresses. The suction of a soil can be represented by the following equation,

$$s = u - \alpha p \quad (1-16)$$

where, p is the overburden pressure.

α is the compressibility factor and it varies between 0 and 1.

It has been demonstrated that α is given by the derivative of the shrinkage curve of the soil (Croney et al., 1958). If there is no equipment available to obtain a shrinkage curve the following relationship may be used,

$$\alpha = 0.027PI - 0.12 \quad (1-17)$$

where, PI is the plasticity index of the soil.

The moisture content can be directly read off from the soil-moisture characteristic curve using the value of suction calculated.

1-3 Pore Size Distribution

The measurement of pore size distribution allows the engineer to obtain a quantitative measure of the fabric of soils. It has frequently been noted that the grain size criteria are insufficient to predict the behavior of soils under varied conditions. Since it is the pore sizes which affect the permeability and change during compression, sample disturbance, and swelling, the study of pore size distribution is an important tool to the engineer.

1-3.1 Applications

Pore size distribution studies have been of interest to researchers in various fields including chemical engineering, petroleum engineering, soil science, and geotechnical engineering. It has been used to predict the permeability by Purcell(1949), Childs et al.(1950), Marshall(1958), Millington and Quirk(1959), Green and Corey(1971), Garcia-Bengochea(1978), Juang(1981), and others.

Silveria(1965) combined pore size distribution calculations with probabilistic modeling to study the problem of fine particles passing through protective sand filters. Sridharan(1968) used pore size distribution studies to calculate the negative pore pressures in partly saturated clays in an effort to better understand the shear

strength of partly saturated soils by examining the soil structure.

Ahmad(1971) related pore size distribution to the strength of clayey soils. Reed(1977) correlated frost heave rate of compacted soils with pore size distribution. The application of pore size distribution in many branches of engineering has been comprehensively discussed by Ahmad(1971) and Garcia-Bengochea(1978).

Several methods are available to measure the pore size distribution. The gas adsorption technique, capillary rise test, pressure plate suction test, and mercury intrusion are among the commonly used methods. Bhasin(1975) presented a critical review of the various techniques available and concluded that only the mercury intrusion method is capable of measuring the entire range of pore sizes of fine grained soils. The mercury intrusion method is used in this study following the lead of previous researchers of Purdue University.

1-3.2 Theory, Assumptions, and Limitations

The basis of the mercury intrusion method, as originally conceived by Washburn(1921), and subsequently applied by Ritter and Drake(1945), rests on the principle that a non-wetting fluid will require external pressure to intrude a porous medium. The pressure required depends on

the contact angle, the pore shape, and the surface tension of the liquid. For cylindrical pores Washburn suggested the following relation:

$$P = \frac{4 T \cos \alpha}{d} \quad (1-18)$$

where, P = required pressure

T = surface tension of the intruding fluid

α = contact angle between the solid and the fluid

d = diameter of the pore

Mercury has been found to be the best intruding fluid because of its low vapour pressure, inertness, and non wetting property to most surfaces (Winslow and Diamond, 1970). Diamond (1970) measured the contact angle for mercury on various minerals by the sessile drop method. He suggested that contact angle on kaolinite or illite was within one degree of 147 degrees, and on montmorillonite was within one degree of 139 degrees.

With the assumption of constancy of the surface tension and contact angle, Washburn's equation implies that as pressure increases mercury will be intruded into progressively smaller pores. For each pressure increment, mercury is forced into the accessible soil pores of a diameter larger than or equal to that calculated from equation (1-18) at the corresponding pressure. Intruded

volume is recorded along with the pressure as the experiment progresses.

The most important limitation of this method is that the pore diameter measured at a given pressure is the diameter of the channel leading into the pore, which could be smaller than the actual size of the pore (Ritter and Drake, 1945). As the result of this "ink bottle" effect, the pore diameters measured are referred to as "limiting pore diameters". Cebeci et al. (1978) attempted to evaluate the arrangement of ink bottle pores by a second intrusion technique. However, obtaining the true pore size distribution is still a difficult task. This problem is of minor importance in the case of flow through porous media, because the flow channels through which the water has to flow are probably equivalent to those intruded by mercury.

Other assumptions or factors to be considered for mercury intrusion, as listed by Garcia-Bengochea (1978), are:

- 1) Only the pores accessible from the outside of the sample are penetrated.
- 2) The minimum pore size is dependent on the pressure capacity of the porosimeter.
- 3) The soil is considered to be incompressible during pressurization and does not break down.
- 4) The contact angle and surface tension values are assumed to be constant during pressurization.
- 5) The mercury will not react with the soil during

intrusion.

- 6) Cylindrical pore shapes are assumed to calculate pore diameter.

A detailed discussion of the assumption and sources of error of the mercury intrusion technique can be found in Ritter and Drake(1945), Rootare(1968), Winslow(1969), Diamond(1970), Bhasin(1975), Garcia-Bengochea(1978), Kenney (1980), Reed et al.(1980), and Juang(1981).

1-4 Soil Drying Methods

The measurement of pore size distribution of a soil by mercury intrusion technique requires dry samples. The dehydration process may cause shrinkage, expansion, cracking, fabric reorientation or even mineralogical changes. Several methods have been developed to dehydrate the samples. The amount of change in gross volume has been the most common criterion used to monitor the fabric changes. Mineralogical changes can be detected by differential thermal analysis, X-ray diffraction, and scanning electron microscopy.

Air or oven drying is the simplest method of dehydration and was used by Diamond(1970) and Sridharan et al.(1971) for a compacted clay. The authors concluded that oven drying method did not affect their results adversely. However, they noted air or oven drying is not an effective

drying method for many saturated or non-saturated clayey soils, because of the large shrinkage that usually occurs with drying.

Critical region drying is the most complex procedure of dehydrating soils, and was discussed by Bhasin(1975). The method consists of elevating the temperature and pressure of a saturated soil specimen in a controlled manner to the critical region of water, at which the gas and liquid exist in a single phase. Once the critical region is reached, the pressure and temperature of the sample are slowly reduced to atmospheric in a way that water in the sample remains in the gas phase. Thus, the shrinkage forces caused by air-water menisci are eliminated. However, the minerology of the soil could be changed by the high temperatures and pressures used to reach the critical region of water.

The fluid replacement method is another drying technique discussed by Tovey and Yan(1973). This method involves replacing the pore water with another liquid of low surface tension, usually an organic liquid. This liquid is removed by air or oven drying. Since the shrinkage forces are small because of the low surface tension, there will not be substantial change in the soil fabric. However, it was found that swelling frequently accompanies fluid replacement. For this reason and because of the complication of the process, fluid replacement is not considered suitable for large investigations.

Freeze drying is the method used in this study as recommended by Zimmie and Almaleh(1976). This method consists of quickly freezing a small soil specimen to cryogenic temperatures, followed by vaccum drying the frozen sample to remove water by sublimation. The quick freezing prevents frost heaving by minimizing ice crystal nucleation and water migration. Sublimation eliminates the formation of air-water menisci, and hence shrinkage forces which alter the soil structure. Zimmie and Almaleh(1976) pointed out that vaccum drying could be performed at room temperature without a refrigerant, because sublimation is an evaporative process accompanied by cooling, so, although the specimen container is exposed to room temperature the sample temperature will stay below freezing. By adopting his recommendation the drying technique is simplified and accelerated.

If properly conducted, freeze drying of soils has been shown to be a superior method for removing water by many researchers including, Diamond(1976), Tovey and Yan(1973), and Zimmie and Almaleh(1976). The volume changes are generally less than 5 percent. For this reason and its relative simplicity freeze drying was chosen for use in this study.

2 - SOILS STUDIED

Two types of soils were used in this study: an artificial mixture of soil materials, and number of naturally occurring soils. The artificial mixture is composed of a natural silt and a commercial kaolin clay. The artificial mixture was used to compare with the water-permeability values obtained by Garcia-Bengochea(1978) for the same materials. These soils were chosen by him to represent the natural silty clays which are frequently used in earthwork construction.

The silt was taken from a natural loess deposit near the Wabash River in southwestern Indiana. The soil was excavated from the second bench level on the east side of U.S.Highway 41, about one mile south of Patoka, Indiana. The silt was air dried and passed through a No. 40 U.S standard sieve before testing. X-ray diffraction analysis showed that the silt was composed primarily of quartz and dolomite with small amounts of calcite and feldspar also present. The silt was found to contain 1 to 3 percent of clay particles. A separate analysis on the clay revealed the presence of illite, kaolinite, and montmorillonite with a possible trace of vermiculite(Garcia-Bengochea, 1978).

The kaolin used in this study is the commercially available Edgar plastic kaolin. It is processed to remove material coarser than 40 μm in size, dried in a tunnel dryer to 300° to 450°F, and then pulverized. The manufacturer states that 99.5 percent of the clay mineral composition is kaolin with the remainder being quartz or mica.

Three blends of silt and kaolin were tested:

90% silt - 10% kaolin

70% silt - 30% kaolin

50% silt - 50% kaolin

Grain size distribution curves and soil classification properties for the silt and for each of these mixtures are shown in Figure 2 and Table 2 respectively.

The natural soils used in this study were taken from various places in Illinois, and provided to the author by Professor W.J.Dempsey of the University of Illinois. A complete description of these soils can be found in Janssen and Dempsey(1980). The relevant properties of the soils used and their code designations are shown in Table 3. The soils chosen have Activities varying from 0.13 to 2.2. It was hoped that the variation in Activity will reflect the various degrees of soil-water interaction and would allow the examination of a much larger range of minerologic effects. X-ray diffraction analyses were performed on most of these soils and the results are given in Table 4. As

Figure 2 Grain Size Distributions for Silt-Kaolin Mixtures (After Reed, 1977)

TABLE 2 CLASSIFICATION OF ARTIFICIAL MIXTURES OF SILT AND KAOLIN

	Specific Gravity G_s	Liquid Limit (%)	Plasticity Index (%)	Clay Size Fraction (% < 2 μm)	Soil Classification	
					AASHTO ASTM D3282-73	Unified ASTM D2487-69
Natural Silt	2.73	-	NP	2	A-4(0)	ML
90% Silt and 10% Kaolin	2.72	-	NP	9	A-4(0)	ML
70% Silt and 30% Kaolin	2.71	25.3	7.0	21	A-4(5)	CL-ML
50% Silt and 50% Kaolin	2.69	36.7	9.7	33	A-4(11)	ML

TABLE 3 CLASSIFICATION OF NATURAL SOILS STUDIED

Soil Name	Specific Gravity G_s	Liquid Limit %	Plasticity Index %	Clay Size Fraction (% < 2 μ m)	Soil Classification	
					AASHTO	Unified
ALVIN-B	2.68	21	2	15	A-4(8)	ML
AVA-B	2.68	33	11	23	A-6(11)	CL
BRYCE-A	2.63	51	22	10	A-7-6(16)	MH
CATLIN-B	2.71	47	19	29	A-7-6(22)	ML
CISNE-B	2.69	53	29	42	A-7-6(29)	CH
HERRICK-A	2.52	41	12	13	A-7-6(14)	ML
HOSNER-A	2.60	34	5	3	A-4(6)	ML
HOSMER-B	2.66	47	22	30	A-7-6(25)	CL
RICHVIEW-B	2.67	36	11	29	A-6(10)	ML
SABLE-B	2.65	51	27	31	A-7-6(30)	CH
STOY-A	2.62	31	8	6	A-4(7)	ML

Note: 1) Symbols following the soil names pertain to the soil horizon.

2) Group index of the soil is given within the paranthesis.

Table 4 Results of X-ray Diffraction Analysis on Natural Soils Tested

Soil	Minerals Present
ALVIN-B	Illite, Kaolinite, Vermiculite, and random mixed layer Vermiculite and Illite
AVA-B	Kaolinite, Illite, Montmorillonite
CISNE-B	Kaolinite, Montmorillonite
HERRICK-A	Kaolinite, Illite, Montmorillonite, Trace of Vermiculite
HOSMER-A	Kaolinite, Illite, Vermiculite, Random Mixed Layer Vermiculite and Illite
HOSMER-B	Montmorillonite, small amounts of Illite, Halloysite, and Kaolinite
RICHVIEW-B	Kaolinite, Illite, Montmorillonite, Random Mixed Layer Vermiculite and Illite
SABLE-B	Kaolinite, Strong Montmorillonite, Illite
STOY-A	Kaolinite, Illite, Montmorillonite-disordered, Mixed Layer Vermiculite and Illite

testing progressed it was found that the results of X-ray diffraction analysis were not much of use for correlation purposes. Consequently, this analysis was not continued for rest of the soils.

3 - APPARATUS AND EXPERIMENTAL PROCEDURE

3-1 Soil Mixing and Curing

The mixing of silt and kaolin was achieved using a Patterson-Kelley liquid-solid mechanical blender. The blender, shown in Figure 3, consists of a rotating V-shell inside which is a high speed rotating dispersion bar from which deionized water is sprayed. A graduated cylinder is connected to the dispersion bar through a stop cock which controls the amount of water to be sprayed.

To use the blender, 2 Kg of the air dried silt-clay combination was first dry mixed for about 10 minutes. Deionized water was then added at a rate of 50 to 75 ml per minute. After the desired quantity of water was added, the blender was stopped and soil was scrapped off the inside walls of the shell. Following scraping, the mixer was run for about 7 minutes, followed again by scraping and another 7 minutes mixing period. The soil was then removed from the shell, sealed inside a polyethylene bag, and cured for two days.

When adding water to the dry mix, experimentation indicated that adding 0.5 percent less water than calculated

Figure 3 Patterson-Kelley Blender

gave within 0.25 percent of the desired moisture content. This procedure was adopted because the silt and kaolin were at some small initial water content in the air dried state.

3-2 Compaction

3-2.1 Apparatus

An electrically driven, semi-automatic kneading compactor(Figure 4) made by August Manufacturing Company was used to compact the silt-kaolin mixture. The sample is compacted by a triangular shaped foot with curvature on sides. The pressure applied by the foot is controlled by a pneumatic-hydraulic system with an air regulator and a pressure gauge. The sample holder rotates 60 degrees between each tamp in order to achieve uniform compaction.

The pressure applied on the soil by the foot is not directly measured. Gaudette(1960) and Reed(1977) have determined calibration curves for converting gauge pressures to the actual foot pressures applied to the soil. However, Garcia-Bengochea(1978) suggested that these curves are not unique and considerable variations in the foot pressure may occur with seasonal variations in temperature and humidity. He further stated that if the foot was not at the bottom of its stroke before tamping started, the first few tamps gave exceedingly high foot pressures. Bailey(1976) and

Figure 4 Kneading Compactor

Gaudette(1960) give further details about the operation of the kneading compactor.

Considerable difficulties were encountered in replicating the dry densities obtained by Garcia-Bengochea(1978) because of the above mentioned problems.

3-2.2 Procedure

As the results of Garcia-Bengochea(1978) were used in this study, the procedure adopted by him to compact his samples were used. The samples were compacted in a mold 4.0 in. in diameter and 1/30 cu.ft.(approximate) in volume(ASTM D 698). A circular filter paper of diameter 4 in. was placed in the bottom of the mold to prevent the soil from adhering to the base plate. The soil was placed and compacted in five layers of approximately equal thickness. Thirty tamps of the compaction foot were applied to each layer. Before adding a fresh layer of soil the previously compacted layer was scarified in order to prevent separation at the contact between layers. The fresh soil was tamped three times with a piston before compaction began in order to densify the soil just enough to prevent the mechanical foot from punching through the layer.

Once the compaction procedure was completed, the collar was removed and the soil was trimmed flush with the top of the mold. The weight of the mold and sample was noted.

Then the sample was extruded from the mold, and cut into small cubes for freeze drying. Trimmings were used to obtain the water content.

Several problems as noted by Garcia-Bengochea(1978) were encountered during compaction. It was not possible to compact the soils with water content 3 to 4 percent greater than the optimum water content; the soil tended to stick to the foot during its upward stroke, preventing effective compaction. Also when the moisture content was slightly above the optimum water content, the soil adjacent to the foot heaved and cracked.

The natural soils obtained from Illinois were provided in compacted form. The soils were compacted in a commercially available Tempe pressure cell (5.35 cm. in I.D and 3.0 cm. in height). The samples were prepared by mixing soil and water to give the optimum water content for Standard Proctor compaction(ASTM D 698). The soil was then placed into a Tempe cell and compacted by 20 blows of a 1.5 lb weight falling 12 in. The sample was then inverted and compacted an additional 20 blows on the other side. This procedure gave the density similar to that specified by ASTM D 698. A detailed description of the procedure can be found in Janssen and Dempsey(1980).

3-3 Freeze Drying

The freeze drying procedure as suggested by Zimmie and Almaleh(1976) was used in this study.

3-3.1 Apparatus

The apparatus used in this study was assembled by Reed(1977) and the following description is taken directly from his work. Figures 5 and 6 show the basic components of the freeze drying equipment which include

- 1) Wire cage to hold the samples during freezing and sublimation.
- 2) Large Dewar flask containing liquid nitrogen into which the sample and cage are dipped.
- 3) Dessicator with inside wire support from which sample cage is suspended during sublimation.
- 4) Vacuum pump capable of evacuating to less than 0.01 mm of mercury.
- 5) Condensor, which is connected between the dessicator and vacuum pump in order to prevent vapor from the soil entering the pump. Liquid nitrogen contained in the dewar flask was used to cool the condenser.

3-3.2 Procedure

After compaction the sample was extruded from the mold using an hydraulic extruder. The extruded sample was

Figure 5 Sample Cage Suspended in Desiccator
(From Reed, 1977)

Figure 6 Freeze Drying Apparatus with Vacuum Pump,
Condenser and Desiccator (From Reed, 1977)

dissected into several pieces using a wire saw. Small cube samples 8 mm on a side were trimmed from these pieces using a single edge razor blade. The trimmings were used to determine the water content of the sample. About ten small specimens were cut from top, bottom, and middle portions of the sample. The trimmed samples were placed in a cage and lowered into liquid nitrogen. They remained in liquid nitrogen for approximately 10 min. To prevent air bubbles from adhering to the sides of the specimens, and hence insulating the samples from liquid nitrogen, the wire cage was moved up and down during its stay in liquid nitrogen.

After about 10 min. the vacuum pump was started and the wire cage was quickly transferred to the dessicator for vacuum drying. Vacuum was maintained at approximately 0.1 mm of mercury while sublimation took place. Zimmie and Almaleh (1976) found that 5 to 10 hr. of vacuum drying would be sufficient for kaolinitic soils, and 9 to 10 hr. would be sufficient for montmorillonitic soils. Since a variety of soils were used in this study, a minimum 10 hr. of vacuum drying was used (usually the vacuum pump was run overnight). Once sublimation was completed, the samples were removed from the wire cage, placed in labeled bottles, and stored in a dessicator containing anhydrous calcium sulphate (commercial name "Drierite") which removed any remaining moisture.

3-4 Pore Size Distribution

The apparatus and procedure used in this study to determine the pore size distribution is essentially the same as that used by the previous Purdue researchers Ahmed(1977), Bhasin(1975), Reed(1977), and others. Thus, only a brief description of the apparatus and procedure will be given below.

3-4.1 Apparatus

The apparatus used in the measurement of pore size distribution is composed of a penetrometer; a filling device; a vacuum pump; a McLeod gauge; a mercury manometer; a control board; and an Aminco porosimeter.

The penetrometer (Figure 7) consists of a glass tube attached to a finely-calibrated capillary stem. The stem is calibrated in 0.002 ml increments and has a capacity of 0.02 ml. The bulb is approximately 6.1 ml in capacity and is used to house the sample. A greased stainless steel cap and a teflon fastener are used to seal the bulb.

The filling device is a two chambered glass tube which holds the penetrometer in a horizontal position during filling and low pressure intrusion. The filling device is connected through a pressure control board to a vacuum pump, McLeod gauge, mercury manometer, and a bleeder valve. The McLeod gauge is used to measure pressures below 1 mm of

Figure 7 Penetrometer: Disassembled and Assembled with Sample

mercury and the manometer is used to measure pressures between 1 mm of mercury and atmospheric pressure. The arrangement of the system is shown in Figure 8.

An Aminco porosimeter(Figure 9) is used to apply pressures above atmospheric pressure. The porosimeter holds the penetrometer vertically in a chamber, and applies pressures up to 15000 psi with an electrically driven hydraulic pump using ethanol as the pressurizing fluid. Volume changes as small as 0.0001 ml are measured using an electro-mechanical sensing device which travels in the stem of the penetrometer. Two Bourdon pressure gauges of capacities 1000 psi and 15000 psi are used to measure the intruding pressure.

3-4.2 Procedure

Following freeze drying, the samples were trimmed with a razor blade in a method intended to produce tensile failures on the surface to keep surface pores from being smeared shut. After trimming, the sample was weighed to the nearest 0.0001 g, then sealed in a penetrometer and weighed again. The penetrometer was then placed in the filling device and sealed around the stem with the bulb protruding. The vacuum pump was then used to evacuate the system to less than 0.02 mm of mercury, a process which usually took 30 to 45 min.

Figure 8 Filling Device, McLeod Gauge and Control Board

Figure 9 Aminco Porosimeter

After evacuation of the system was complete, the penetrometer was filled with mercury. This was accomplished by rotating the filling device so that the mercury it contained covered the opening at the end of penetrometer stem. The vacuum pump was then turned off, air was bled into the system to a pressure of approximately 20 mm of mercury. This pressure is called the filling pressure. Raising the pressure forced mercury into the stem and bulb, and surrounded the sample to be intruded.

After the mercury completely filled the penetrometer stem, the filling device was rotated again back to its original position. This broke off the column of mercury near the end of the stem producing an initial stem reading which was recorded along with the filling pressure. This pressure was then raised in increments according to the equation $P_i/P_{i-1} = 10^c$, where c was 0.18, to produce a logarithmically equal class width as suggested by Garcia-Bengochea(1978).

When atmospheric pressure was reached, the penetrometer was removed from the filling device and weighed in order to find the amount of mercury in the stem. A final stem reading was taken with the axis of the penetrometer horizontal; it was then placed in the porosimeter. An initial reading of volume intruded was taken using the electro-mechanical probe of the porosimeter. These steps allow for a transition from low pressure to high pressure

readings. The pressure was increased incrementally maintaining intervals as for the low pressure readings until the pressure was just below the capacity of 15000 psi. Probe readings were taken after each increment of pressure was added. Only a short time (about 15 sec) was found to be necessary to complete each incremental intrusion. This process (above atmospheric) was known as high pressure intrusion.

3-5 Air Permeability

3-5.1 Apparatus

The apparatus (Figure 10) used in this study to determine air permeability was developed by Serracin(1980) and modified by the author to allow for the use of a drying mechanism. The schematic diagram of the apparatus is shown in Figure 61, Appendix B. "The principle of the apparatus is that the flow rate is measured by following the decay of a pressure differential imposed across the sample. A knowledge of the decay rate, the sample dimensions, and certain apparatus constants permits the calculation of the permeability " (Dolch, 1956).

The components of the apparatus are: an u-tube, one end connected to a glass bulb and the other end to a stopcock; a sample holder; a meter stick; and a plastic tube(commmercially known as dry tube) filled with a drying

Figure 10 Air Permeability Apparatus

agent. Mercury or water is used as the manometer fluid depending on the permeability of the sample.

The glass bulb at one end of the u-tube is used to support the sample holder during the testing. It is tapered inside to facilitate housing the sample holder, which is also tapered to fit inside the bulb. The stopcock is used to maintain a pressure difference before starting the test. The air is dried by allowing it to pass through the drying agent before it enters the sample. The meter stick is used to measure the elevation of the manometer liquid column during the testing.

3-5.2 Procedure

Following freeze drying, the dimensions of the sample were measured using a vernier caliper. The sample holder was placed on a clean glass plate, and the sample was placed in position in the sample holder and sealed in place by pouring hot paraffin. Then the sample holder with glass plate was placed in a dessicator until the paraffin hardened. In this study, it was found that applying a thin film of rubber cement to the sides of the sample and the sample holder before pouring paraffin gave a better seal and grip. Also to avoid excessive shrinkage, hot paraffin was poured when its temperature was about 3°C above its melting point.

In the meantime a pressure difference in the manometer was established by applying a pressure to the stopcock side of the u-tube and maintained by closing the stopcock. The sample holder was then removed from the dessicator and a thin film of vacuum grease was applied to the outside before placing it in position in the glass bulb. The dry tube was connected to the top of the sample holder via a cork and a tube.

The stopcock was then opened and the rate of movement of the manometer level was recorded using a stop watch. It was found that the time required for each test varied from one minute to one hour depending on the permeability. The equation used to calculate the permeability and its derivation are given in Appendix B.

4 - RESULTS AND DISCUSSION OF RESULTS

4-1 Compaction

Three levels of compaction effort were used for the silt-kaolin mixture. The medium effort was chosen by the previous researchers to obtain an optimum dry density for 90% silt- 10% kaolin mixture similar to that obtained by AASHTO T99-70 (ASTM D 698) procedure(i.e. Standard Proctor) for the same soil. The high compaction effort was used to approximate that of the modified Proctor compaction procedure(ASTM D 1557). A low compaction effort was also used.

In this study, samples of the silt-kaolin mixture were prepared at water contents selected to give a spread in the permeability values. It was not possible to replicate the dry density for some samples as obtained by the previous researchers because of the difficulties discussed in Section 3-2.

The code designations used to identify the silt-kaolin mixtures are given in Table 5. The code gives the soil type, the compaction effort, and water content relative to its optimum water content.

Table 5 Sample Code Designation of Artificial Mixtures
 of Silt and Kaolin

Soil Type

S9 - 90% Silt and 10% Kaolin

S7 - 70% Silt and 30% Kaolin

S5 - 50% Silt and 50% Kaolin

Compaction Effort (Gauge Pressure)

L - Low Compaction Effort; 4.0 psi.

M - Medium Compaction Effort; 8.5 psi.

H - High Compaction Effort; 40 psi.

Moisture Condition

O - Near Optimum Water Content

D - Dry of Optimum Water Content

W - Wet of Optimum Water Content

Example

S5MD: 50% silt and 50% kaolin compacted at 8.5 psi
 gauge pressure and dry of optimum water content.

All natural soils used in this study obtained from Illinois were compacted at their respective optimum water content. The compaction procedure discussed in Section 3-2.2 was used to approximate the maximum dry density obtained by the procedure of ASTM D 698 for the same soil.

Table 6 gives the sample codes and the compaction parameters of all the soils tested. Figures 11, 12, and 13 present the compaction curves for silt-kaolin mixtures and the location of each of the sample points. The compaction curves were obtained by Garcia-Bengochea(1978).

4-2 Freeze Drying

The freeze drying process used in this study was simple and suitable for drying a large number of samples at one time. Several initial measurements indicated that volume change during freeze drying was within four percent as suggested by Garcia-Bengochea(1978); hence no additional checks were made beyond the initial ones.

4-3 Permeability

4-3.1 Air Permeability

The air permeability was measured by a falling head permeability apparatus. A pressure gradient as large as 4000 kN/m³ was used. The calculation procedures are

Table 6 Compaction Parameters of Soils Tested

SAMPLE CODE	MOISTURE CONTENT (PERCENT)	DRY DENSITY (lb/ft ³)
S9HW	13.5	114.8
S9MW	16.8	107.6
S7HO	12.97	118.7
S7MO	14.3	113.9
S7LO	18.5	109.3
S5MO	17.7	110.7
S5MD	16.5	113.1
S5LD	18.01	109.0
S5LO.	19.6	106.1
ALVIN-B	12.8	117.4
AVA-B	19.6	106.7
BRYCE-A	24.4	87.2
CATLIN-B	20.8	85.7
CISNE-B	21.6	91.8
HERRICK-A	22.4	94.0
HOSMER-A	20.1	96.5
HOSMER-B	20.3	96.6
RICHVIEW-B	19.6	101.4
SABLE-B	21.6	95.4
STOY-A	17.9	98.4

Figure 11 Compaction Curves for 90% Silt and 10% Kaolin

Figure 12 Compaction Curves for 70% Silt and 30% Kaolin

Figure 13 Compaction Curves for 50% Silt and 50% Kaolin

discussed in Appendix B. The temperature was not controlled during the testing; it was monitored, and appropriate values of viscosity and unit weight of air at that temperature were used in the calculations.

The permeability value assigned to each soil is the average value of permeabilities obtained from three to four samples. For each sample the test was repeated two to three times and the average value was taken as the permeability of the sample. When the permeability test was repeated for the same sample the values of permeability obtained were in close agreement with each other, whereas among samples of the same soil a difference of one order of magnitude was found in some cases.

Figures 14 through 23 show some of the typical plots of flow rate versus pressure gradient. It is clear that Darcy's law is obeyed for gases. However, a small intercept on the gradient axis was obtained in many cases. Two possible explanations can be offered. One is that during testing the manometer level varied very rapidly for soils of large permeability and, hence, the recorded readings may be slightly in error. This under-estimation of the rate of flow would create a small intercept in the gradient axis. The other possible error could have resulted from the change in the contact angle of the manometer fluid on glass due to atmospheric contamination of the glass as suggested by Olsen(1965). It was found that for a 0.635 cm diameter

Figure 14 Air Flow Velocity Vs Pressure Gradient for Alvin-B

Figure 15 Air Flow Velocity Vs Pressure Gradient for Ava-B

Figure 16 Air Flow Velocity Vs Pressure Gradient for Hosmer-A

Figure 17 Air Flow Velocity Vs Pressure Gradient for Stoy-A

Figure 18 Air Flow Velocity Vs Pressure Gradient for S9MW

Figure 19 Air Flow Velocity Vs Pressure Gradient for S5L0

tube, the possible error in the gradient assuming contact angles of 36° and 76° for receding and advancing meniscus respectively was about 3.21 KN/M^3 . The combined effects of these two factors could have yielded a small intercept on the gradient axis.

It was also found that drying of air had no significant effect on the permeability of the soils. In order to check this, some samples were first tested with dried air. Then the samples were left in the atmosphere for one day and tested again. As can be seen from Figures 20 through 23 no significant difference in permeability was found. It is also possible that the method used to dry the air was ineffective.

The physical permeability values obtained were not corrected for probable gas slippage. As discussed in Section 1-1.2, gas slippage tends to give higher values for permeability. An examination of the data obtained by Dolch(1956) for samples of permeability comparable to that used in this study suggested that the (true) physical permeability at infinite mean gas pressure is about 20 to 35 percent lower than that obtained at a mean pressure of one atmosphere. This variation is comparable to the usual variability in the measured permeabilities; thus, it was decided to not include such a correction.

Figure 20 Air Flow Velocity Vs Pressure Gradient for S5MD

Figure 2 I Air Flow Velocity Vs Pressure Gradient for S5MD

Figure 22 Air Flow Velocity Vs Pressure Gradient for S7HD

Figure 23 Air Flow Velocity Vs Pressure Gradient for S7HD

4-3.2 Water Permeability

The water permeability values used in this study for silt-kaolin mixtures were obtained by Garcia-Bengochea(1978). He used a closed system, falling head apparatus to measure the permeability. For some samples the permeability changed with hydraulic gradient (S7LO, S7HO AND S5LO); thus, Darcy's law was not obeyed for those samples. Experimental errors were given as the reasons. The permeability values assigned to each of the samples were calculated from an average of six to eight measurements from the stabilized portion of the permeability-hydraulic gradient curves. Even though Garcia-Bengochea did not mention it in his thesis, particle migration at the beginning of the test could have resulted in lower values of permeability.

For samples whose compaction variables could not be replicated in this study, the water permeability values were obtained by calculating the pore size parameters and then using the prediction equation developed by him to calculate permeability.

The water permeability values of the natural soils tested were obtained by Janssen and Dempsey(1980). They used a constant head permeability apparatus. The permeability assigned to each soil is an average from three specimens.

4-4 Pore Size Distribution

4-4.1 Data Reduction

The pore size distribution was determined from the pressure and intrusion data using Equation (1-18). The use of this equation requires the knowledge of the surface tension and contact angle of the mercury. The surface tension was assumed to be 484 dynes/cm. A contact angle of 147° was used for the silt-kaolin mixture and natural soils of high kaolin content. For the soils of high montmorillonite content a contact angle of 139° was used (Diamond, 1970).

In order to reduce the mercury intrusion data, the computer program developed by Reed(1977) was used. This program includes correction for compression of air and mercury during intrusion. This program was modified in order to plot both the porosity density function and the normalized cumulative distribution function as will be discussed in the next section. A listing of the program used is given in Appendix C.

4-4.2 Presentation of Data

The data from the mercury porosimeter is usually presented in the form of cumulative and differential pore size distribution curves. A detailed discussion on the

presentation of data can be found in Garcia-Bengochea(1978) and Juang(1981). In the present study the following method was chosen to present the data.

- a) Cumulative distribution curve: at a given diameter, the volume intruded is normalised to 100 percent of the total pore volume and plotted against the logarithm of the diameter. The use of total pore volume to normalize the distribution is justified by the fact that more than 95 percent of the pore volume was intruded in the majority of the samples tested.
- b) Differential distribution curve: even though the pore diameter is a continuous variable, the mercury porosimeter permits measurements at discrete points only. However, the porosity density function obtained from discrete data is used in this study.

The porosity density function is obtained from the discrete data as follows: each pressure increment corresponds to a decrease in pore diameter from d_{i-1} to d_i . The pressure increments are selected so that the difference between $\log d_i$ and $\log d_{i-1}$ is a constant, i.e.

$$\log d_i - \log d_{i-1} = c \quad (4-1)$$

$$d_{i-1}/d_i = 10^c \quad (4-2)$$

where d = pore diameter corresponding to an intrusion pressure P

c = constant

From Equation (1-18), it is evident that intrusion pressure is inversely proportional to the pore diameter.

Therefore,

$$P_i/P_{i-1} = 10^c \quad (4-3)$$

By increasing the pressure of intrusion according to Equation (4-3) and maintaining c constant, logarithmically equal class width can be obtained. The volume of pores intruded between diameter d_i and d_{i-1} is calculated from the porosimeter readings. This incremental volume is divided by the class width(c), normalised to 100 percent of the total pore volume, and plotted at the midpoint of the class width. The midpoint D will be obtained by the following equation,

$$\log D = (\log d_i + \log d_{i-1})/2 \quad (4-4)$$

$$D = \sqrt{d_i d_{i-1}} \quad (4-5)$$

The porosity density function, $f(d)$, can be obtained by connecting the values of D , $f(D)$ by straight line segments. The smaller the value of c used the better the actual density function is approximated. In this study a value of 0.18 was used for c . Juang(1981) found that the finite different approximation, as used in this study, compares well with the density function obtained from direct differentiation of the cumulative distribution curve.

Garcia-Bengochea(1978) plotted the porosity frequency and suggested that distortion in the curves may occur unless logarithmically equal pressure increments during intrusion

are used. In this study it was found that by plotting the porosity density function the distortion, which could arise from unequal pressure increments, can be kept to a minimum.

The pore size parameters were, however, calculated from the discrete values obtained directly from the porosimeter measurements. This was done in light of the fact that the numerical integration of the porosity density function to get the pore size parameters did not improve the accuracy substantially.

4-4.3 Comparison of Pore Size Distribution Curves

The pore size distribution curves are shown on Figures 24 through 26 and in Appendix A on Figures 42 through 60. It can be seen that about two-thirds of the samples tested exhibit a bi-modal characteristic and the remaining one-third of the samples show single modal characteristics. Bi-modal and single modal characteristic were found in both the natural soils and the artificial mixture of silt and kaolin.

For the silt-kaolin mixtures showing the bi-modal characteristic, the smaller pore mode occurred closer to 0.1 or 0.2 μm and the larger pore mode occurred between 0.5 and 10 μm . However, the majority of the silt-kaolin mixtures were found to have single modal characteristic, and the pore mode occurred between 0.1 and 0.6 μm except for soil S9MW for which it occurred at 0.2 μm . The findings for soils having

Figure 24 Pore Size Distribution Curves for 70% Silt-30% Kaolin Compacted at Optimum Water Content for Three Efforts

Figure 25 Pore Size Distribution Curves for 50% Silt-50% Kaolin Compacted at Medium Effort

Figure 26 Pore Size Distribution Curves for 50% Silt-50% Kaolin Compacted at Low Effort

bi-modal characteristic generally agree with those of Garcia-Bengochea(1978) whose soils were all silt-kaolin mixtures. He stated that all of his soils exhibited bi-modal characteristics; however, a close examination of his data suggest that some of his soils did not exhibit a very distinct bi-modal characteristic.

All the natural soils tested in this research exhibited bi-modal characteristic except one. The smallest pore mode occurred between 0.4 and 1.0 μ m, and the largest pore mode occurred between 10 and 100 μ m. For the soil showing the single modal characteristic, the pore mode occurred at 0.5 μ m. White(1980) found that the natural soil he tested exhibited single modal characteristics; however, he tested only one type of natural soil. No generalization about the bi-modal characteristic of natural soils is believed appropriate because even one of the natural soils tested in this study exhibited single modal characteristics. This question is intriguing and does deserve further study.

Figure 24 shows the effect of different compaction energy levels at the respective optimum water contents for 70% silt-30% kaolin mixture. The magnitude of the peak at the larger pore mode is reduced as a result of higher compaction energy; also, the magnitude of the peak at smaller pore mode is increased. This seems to support the concept of the deformable aggregate model. The smaller pore mode is not very distinct for sample S7L0; however, the

smaller pore mode remains close to $0.1\mu\text{m}$. The air permeability decreases with increasing energy level, but the values of permeability are not very different.

Figures 25 and 26 show the effect of water content at the same energy level for 50% silt-50% kaolin mixture at two different compaction energy levels. When the water content is increased the magnitude of the peak at pore mode is reduced for S5M0. At low compaction energy level the magnitude of the peak for S5L0 is reduced but shifted to the right. This may be due to the sample disturbance as it was not possible to cut a small undisturbed sample of S5L0 because of its higher water content. The air permeability at water content dry of optimum is slightly higher than that at optimum.

Generally the results obtained for silt-kaolin mixture followed the trend of the results from Garcia-Bengochea(1978).

4-5 Relation between Pore Size Distribution and Permeability

Previous researchers including Taylor(1948) and Lambe(1951) attempted to correlate logarithm of permeability with void ratio. Garcia-Bengochea(1978) showed that such a relationship is not valid for compacted fine grained soils. It can be seen from Figure 27 that such a relationship also is not valid for air permeability.

Figure 27 Physical Permeability Vs Void Ratio

The models used in this study to predict the permeability are discussed in Section 1-1.4. The relationship between physical permeability (K) and pore size parameter(PSP) is generally of the form

$$K = C_s \text{ PSP}$$

where C_s is a shape factor.

The formulas used to calculate the pore size parameters are shown in Table 1. The integration was carried out both numerically and from discrete data using the method suggested by Garcia-Bengochea(1978). It was found that the values of pore size parameters obtained by these two methods did not differ significantly. Therefore it is believed that as long as the logarithmic pressure (or diameter) increment is kept reasonably small the pore size parameters can be calculated from discrete data. In this study a value of 0.18 was used for the exponent c in the equation $P_i/P_{i-1} = 10^c$.

As can be seen from Equations 1-4 and 1-7, the pore size parameters are very sensitive to the diameter of the larger pores. Some of the larger pores may be just cavities instead of being continuous pores. Therefore, it was necessary to use a cut-off value for the larger pore diameter. A possible criterion to select such a diameter is to find a diameter above which the contribution to the flow from those pores is negligible. Since the soils used in this study are of different types it was not possible to

find a constant cut-off diameter for all the soils. Therefore, it was decided to discard 5 to 10 percent of the pore volume on the larger pore sizes in the calculation. The pore size parameters obtained by omitting 5 percent of the volume did not differ significantly from those obtained by omitting 10 percent of the volume. However, in this study 10% of the pore volume was omitted from the calculations as the pore size parameters obtained by this method gave a better correlation with permeability. The values of pore size parameters are given in Table 7 along with the values of physical permeability of each of the soils.

The pore size parameters from the Capillary and the Marshall model are plotted against the physical permeability obtained from air permeability tests on Figures 28 and 29 respectively. All axes are on a logarithmic scale. It can be seen that the relationship is linear. A linear regression analysis was used to quantify the relationship, and it can be expressed as:

$$\log K = b \log PSP + a \quad (4-6)$$

where a and b are linear regression parameters. Equation (4-6) can be written as:

$$K = 10^a PSP^b \quad (4-7)$$

According to the models used, b is equal to 1 and 10^a is the shape factor. Table 8 presents the linear regression equations and the values of coefficient of correlation (r^2)

Table 7 Permeability and Pore Size Parameters

SAMPLE CODE	CAPILLARY MODEL μm^2	MARSHALL MODEL $\times 10^{-2} \mu\text{m}^2$	K_a $\times 10^{-15} \text{ m}^2$	K_w $\times 10^{-15} \text{ m}^2$
S9HW	2.28	16.10	13.2	2.25
S9MW	2.09	28.70	42.3	3.53
S7HO	0.34	0.574	5.17	0.225
S7MO	0.27	1.68	7.32	0.409
S7LO	0.24	2.37	8.82	0.256
S5MO	0.021	0.062	0.56	0.027
S5MD	0.025	0.059	1.40	0.039
S5LD	0.056	0.438	4.27	0.037
S5LO	0.195	1.390	3.20	0.164
ALVIN-B	35.9	132.0	138	2.24
AVA-B	1.205	4.44	13.6	0.107
BRYCE-A	1021	4958	3510	7.80
CISNE-B	1661	5250	2560	29.3
HERRICK-A	25.5	93.0	219	0.017
HOSMER-A	12.8	52.0	97.8	5.27
HOSMER-B	556.1	1460	990	0.654
RICHVIEW-B	30.5	67.0	162	0.127
SABLE-B	282.2	390	440	5.85
STOY-A	10.3	72.0	68.0	5.07

 K_a =Physical Permeability From Air Permeability Tests K_w =Physical Permeability From Water Permeability Tests

Figure 28 Physical Permeability (Air) Vs Capillary Model
Equivalent Pore Size Parameter

Figure 29 Physical Permeability (Air) Vs Marshall Equivalent Pore Size Parameter

TABLE 3 LINEAR REGRESSION EQUATIONS FOR PERMEABILITY AND
PORE SIZE PARAMETERS (PSP)

Capillary Model:

$$K = (\text{PSP})^{0.72} 10^{-5.25}$$

$$r^2 = 0.971$$

Marshall Model:

$$K = (\text{PSP})^{0.74} 10^{-3.94}$$

$$r^2 = 0.969$$

Units:

$$K - \text{m}^2$$

$$\text{PSP} - \text{m}^2$$

for the models used. The values of r^2 are close to one for both the models. This demonstrates the superiority of models based on pore size distribution to those based on gross volumetric parameters. However, an experimental matching factor is necessary to allow for the different pore shapes and tortuosity.

When the values of physical permeability obtained from water permeability tests were plotted against the pore size parameters, no linear relationship was obtained. However, when only the silt-kaolin mixture was considered a linear plot was obtained. This is probably due to the low activity of kaolin as will be discussed in the next section.

4-6 Effect of Minerology on Permeability

The possible effects of clay-water interaction on permeability are discussed in Sections 1-1.1 and 1-1.2. The ratio of the physical permeability obtained by air and water permeability tests reflects the degree of clay-water interaction. This ratio for the soils tested varied from 5 to 1514, and for the soil Herrick-A it was 12880. For silt-kaolin mixtures the range in permeability ratio was found to be between 5 and 36. This is due to the fact that the silt-kaolin mixture has a low Activity; hence, the mineralogical effect on water during permeation is very low. For the 90% silt-10% kaolin mixture the ratio was between 5 and 12. It should be noted that the air and water permeabilities were

not obtained from the same sample. Thus, the variability in the results and the particle migration during water permeability tests could have led to a difference of one order of magnitude in the physical permeabilities obtained from air and water permeability tests. On the other hand, for the natural soils tested the permeability ratio varied from 13 to 12880. These soils have Activities ranged from 0.13 to 2.2. Also, X-ray diffraction analysis showed that some of these soils have traces of montmorillonite which is a very active mineral.

It has been believed that the effect of adsorbed layer is to reduce the sizes of the pores available for permeation, thus reducing the permeability. To check this, pore size parameters were calculated using pore sizes reduced by an assumed thickness for adsorbed layer, and these parameters were substituted into the predictive equation already obtained to calculate permeability. The permeability thus obtained was much higher than that measured. As discussed in Section 1-1.2, earlier researchers also found that the adsorbed layer does not affect the permeability significantly. Therefore, it was concluded that the adsorbed layer would not have caused such a large difference in permeability with water and air. The electro-kinetic coupling was also found to be insignificant by various researchers including Olsen(1962).

As discussed in Section 1-1.2, Mesri and Olson(1971) also found large differences in permeability of clays to polar and non-polar fluids. The mechanism suggested by them can be extended to the soils tested in this study as follows: The soil particles form stable aggregates and the primary fluid flow takes place in the larger voids between the aggregates. In the presence of water, which is a polar fluid, the aggregates break down and a dispersive structure of low permeability results. The degree of dispersion depends on the physico-chemical properties of soil minerals. Since the increase in activity reflects the presence of highly active minerals, a correlation between permeability ratio and activity was attempted. The values of activity and permeability ratio of the soils tested are given in Table 9 and Figure 30 shows the plot of activity vs logarithm of permeability ratio. Even though considerable scatter is found in the plot, it is useful in predicting the water permeability of active soils from pore size distribution measurements, because all the models proposed so far assume that the pore size distribution does not change during flow.

4-7 Soil Moisture Characteristic Curves

In this study, the mercury intrusion technique was used to obtain the soil-moisture characteristic curve. The theory behind this method is described in Section 1-2.3.

Table 9 Activity and Permeability Ratio

SAMPLE CODE	ACTIVITY	PERMEABILITY RATIO K_a/K_w
S9HW	NA	5.86
S9MW	NA	11.81
S7HO	0.33	22.9
S7MO	0.33	17.9
S7LO	0.33	34.4
S5MO	0.29	20.7
S5MD	0.29	36.0
S5LD	0.29	11.5
S5LO	0.29	19.5
ALVIN-B	0.13	61.6
AVA-B	0.48	127.0
BRYCE-A	2.2	450
CISNE-B	0.69	87.3
HERRICK-A	0.92	12880
HOSMER-B	0.73	1514
RICHVIEW-B	0.38	1275
SABLE-B	0.87	75.2
STOY-A	1.3	13.4

Figure 30 Activity Vs Permeability Ratio

The predicted curves were compared with the ones obtained from experimental method by Janssen and Dempsey(1980) for the same soils. They used the Tempe pressure cell and pressure plate apparatus to obtain the soil-moisture characteristic curve. The highest value of suction measured was 15 bar(1500 KN/M²). Figures 31 through 41 show the soil-moisture characteristic curves obtained by experimental method and those predicted from pore size distribution measurements.

It can be seen from Figures 31 through 36 that the soil-moisture characteristic curve is very well predicted up to a suction of 3000 cm of water whereas for soils ALVIN-B, HERRICK-A and STOY-A the prediction is good only up to 1000 cm of water. However, considerable difference between the experimental and predicted curves were found for soils shown in Figures 37 through 39. An examination of the values of the compacted variables revealed that considerable difference in dry density and water contents existed between the samples used in the mercury intrusion method and the conventional pressure plate test. Also the experimental curves were not replicated. Thus the variability in results could have caused these differences.

The Figures 40 through 41 show that above a suction of 3000 cm of water the experimental and the predicted curves diverge considerably. This can be expected because water retention in the higher suction range is controlled more by

Figure 31 Soil Moisture Characteristic Curves for Ava-B

Figure 32 Soil Moisture Characteristic Curves for Cisne-B

Figure 33 Soil Moisture Characteristic Curves for Hosmer-A

Figure 34 Soil Moisture Characteristic Curves for Richview-B

Figure 37 Soil Moisture Characteristic Curves for Herrick-A

Figure 38 Soil Moisture Characteristic Curves for Stoy-A

Figure 40 Soil Moisture Characteristic Curves for Catlin-B

Figure 41 Soil Moisture Characteristic Curves for Hosmer-B

adsorption and less by structure. The mercury intrusion method does not consider such physico-chemical effects. However, the ability to predict suction values as large as 3000 cm of water is adequate for practical purposes. Moreover, the time required for the mercury intrusion method is minutes as compared to many days for conventional methods to determine soil-moisture characteristic curves. Therefore, this study demonstrates that the equilibrium water content can be predicted and the basis for prediction is readily obtained.

4-8 Frost Heave

At the beginning of this study, it was hoped to correlate the frost heaving rate of compacted silt-kaolin mixtures with effective pore size distribution. The frost heaving rates for such soils were obtained by Reed(1977). However, as discussed in Section 4-6, it was found that the adsorbed layer does not affect the flow of water considerably for silty clays. Therefore, the predictive equation for silty clays as determined by Reed(1977) requires no modifications.

For clays in which permeability is affected by the clay-water interaction further research is required to establish relationship among pore size distribution, frost heaving rate, and physico-chemical variables.

5 - CONCLUSIONS AND RECOMMENDATIONS

5-1 Conclusions

This study concerned artificial mixtures of silt and kaolin as well as samples of naturally existing soils. Recognizing that small specimens were tested in the laboratory, the following conclusions are offered:

- 1) Bi-modal and single modal pore size distributions occur, but no association could be made which would either explain or predict the modality.
- 2) The modality of the pore-size distribution curves appears to be real. Using different numerical procedures for curve plotting and parameter determination did not markedly improve correlations. A differential pore-size distribution curve in the form of the porosity density function is believed clearer for the observer.
- 3) There appears to be no single actual "effective diameter" which characterizes the pore-size distribution sufficiently for correlation purposes. A combination of pore-size distribution characteristics appears necessary to adequately describe the distribution.
- 4) Changes in the compaction variables with which a

given soil is prepared produce discernible and consistent changes in the pore size distribution characteristics. This confirms the results of the previous researchers Garcia-Bengochea(1978) and Juang(1981).

- 5) Darcy's law is obeyed for flow of gases through porous media. The flow velocity varies linearly with the pressure gradient. However, a small threshold gradient is found to exist, but it is believed to be the result of experimental errors.
- 6) Air permeability can be predicted from pore-size distribution parameters. The models for the prediction do not, however, also predict water permeability with any accuracy. A correlation between air and water permeability was accomplished.
- 7) Predictive equations for permeability based upon grain-size parameters are unsuitable for fine grained soils.
- 8) The inability of models for air permeability to predict water permeability is a manifestation of the effect of soil mineralogy, especially the clay content and composition. The larger the Activity of the soil, the larger appears to be the difference between air and water permeability.
- 9) It is believed that the effect of mineralogy upon permeability is through the development of a

dispersed structure during permeation.

- 10) The soil moisture characteristic curve (ie. equilibrium soil water content as a function of soil suction) can be readily predicted from the pore size distribution data. The time required to obtain the data is minutes as compared to many days for suction data. The prediction thus made appears to be adequate for suctions as large as about 25 meters of water.
- 11) The in-situ equilibrium water content of a compacted soil can be predicted provided that an estimate is possible of the location of the free water level in the field installation.
- 13) Pore-size data appears to be a sensitive vehicle for monitoring behavior effects that are controlled by soil fabric.

5-2 Recommendations for Future Research

Further research is needed in the following areas:

- 1) Obtain a correlation among permeability ratio, pore size parameters, and physico-chemical variables such as ion exchange capacity.
- 2) In this study a linear relationship was obtained between air flow rate and pressure gradient. Professor G.Blight(1981-private communication) suggested that the fixed head apparatus tends to give a non-linear relationship. This difference should be examined.
- 3) Influence of pore size distribution on strength and compressibility requires attention.
- 4) Effect of ion-exchange capacity on the soil-moisture characteristic curve at higher suction values should be examined.
- 5) The minerology effect on frost heave rate should be studied for highly active clays.

BIBLIOGRAPHY

1. Adzumi, H. (1937), "Flow of Gases through a Porous Wall", Chemical Society of Japan, Bulletin, 12, pp. 304-312.
2. Ahmed, S. (1971), "Pore Size and Its Effects on the Behavior of a Compacted Clay", MSCE Thesis, Purdue University, West Lafayette, Indiana, June, 200 pp.
3. Bailey, M.J. (1976), "Shale Degradation and other Parameters Related to the Construction of Compacted Embankments", MSCE Thesis, Purdue University, Indiana, August, 230 pp.
4. Barden, L. and Sides, G.R. (1970), "Engineering Behavior and Structure of Compacted Clay", Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, SM4, pp. 1171-1200.
5. Bhasin, R.N. (1975), "Pore Size Distribution of Compacted Soils After Critical Region Drying", Ph.D. Thesis, Purdue University, West Lafayette, Indiana, May, 222 pp.
6. Blight, G. (1971), "Flow of Air Through Soils", Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 97, No. SM4, pp. 607-624.
7. Carman, P.C. (1956), "Flow of Gases Through Porous Media", Academic Press, New York, 182 pp.
8. Cebeci, Z., Demirel, T. and Lohnes, R.A. (1978), "Evaluation of Hysteresis in Mercury Intrusion Porosimetry by Second-Intrusion Method", Research Record No. 675, TRB, pp. 15-20.
9. Collins, K. and McGown, A. (1974), "The Form and Function of Microfabric Features in a Variety of Natural Soils", Geotechnique, Vol. 24, No. 2.
10. Childs, E.C. and Collins-George, N. (1950), "The Permeability of Porous Materials", Proceedings, Royal Society of London, Vol. A201, pp. 392-405.

11. Corey, A.T. (1957), "Measurement of Water and Air Permeability in Unsaturated Soil", Soil Science Society of America Proceedings, Vol. 21, pp. 7-10.
12. Croney, D. (1952), "Movement and Distribution of Water in Soils", Geotechnique, Vol. 3, No. 1.
13. Croney, D., Coleman, J.D. and Black, W.P.M. (1958), "Movement and Distribution of Water in Soil in Relation to Highway Design and Performance", H.R.B. Special Report, No. 40.
14. Croney, D., Coleman, J.D. and Bridge, P.M. (1951), "The Measurement of the Suction of Moisture Held in Porous Materials and Its Relationship to Moisture Content", Report, Road Research Laboratory, Crowthorne, England.
15. Croney, D. and Coleman, J.D. (1953), "Soil Moisture Suction Properties and their Bearing on the Moisture Distribution in Soils", 3rd International Conference on Soil Mechanics and Foundation Engineering
16. Diamond, S. (1970), "Pore Size Distribution in Clays", Clays and Clay Minerals, Vol. 18, pp. 7-23.
17. Diamond, S. (1971), "Microstructure and Pore Structure of Impact-Compacted Clays", Clays and Clay Minerals, Vol. 19, pp. 239-249.
18. Dolch, W.L. (1956), "Permeability and Adsorptivity of Indiana Limestone Coarse Aggregates", Ph.D. Thesis, Purdue University, West Lafayette, Indiana, January, 200 pp.
19. Elzeftawy, A. and Dempsey, B.J. (1977), "Prediction Model for Unsaturated Hydraulic Conductivity of Highway Soils", Transportation Research Record No. 642, Transportation Research Board, Washington, D.C.
20. Garcia-Bengochea, I. (1978), "The Relation Between Permeability and Pore Size Distribution of Compacted Clayey Silts", MSCE Thesis, Purdue University, West Lafayette, Indiana, May, pp. 179.
21. Gaudette, N.G. Jr. (1960), "Application of the Kneading Compactor and Hveem Stabilometer to Bituminous Concrete Design in Indiana", MSCE Thesis, Purdue University, West Lafayette, Indiana, December, 238 pp.
22. Hansbo, S. (1960), "Consolidation of Clay with Special Reference to Influence of Vertical Sand Drains", Swedish Geotechnical Institute Proceedings, No. 18, Stockholm, 160 pp.

23. Hillel, D. (1980), "Fundamentals of Soil Physics", Academic Press, New York, pp. 414.
24. Hodek, R.J. (1972), "Mechanisms for the Compaction and Response of Kaolinite", Ph.D. Thesis, Purdue University, West Lafayette, Indiana, December, 269 pp.
25. Janssen, D.J. and Dempsey, B.J. (1980), "Soil Water Properties of Subgrade Soils", Report No. UILU-ENG-80-2010, University of Illinois, Urbana, Illinois, April, pp. 210.
26. Juang, C.H. (1981), "Pore Size Distribution of Sandy Soils and the Prediction of Permeability", Ph.D. Thesis, Purdue University, West Lafayette, Indiana, August, 237 pp.
27. Kamack, H.J. (1954), "Simple Air Permeability Method for Measuring Surface Areas of Fine Powders", Analytical Chemistry, 26, pp. 1623.
28. Kemper, W.D. (1960), "Water and Ion Movement in Thin Films as Influenced by the Electro-static Charge and Diffuse Layer of Cations Associated with Clay Mineral Surfaces", Soil Science Society of America Proceedings, Vol. 31, pp. 713-715.
29. Kenney, T.C. (1980), "Frost Heaving Rate Predicted From Pore Size Distribution: Discussion", Canadian Geotechnical Journal, Vol. 17, No. 2, pp. 332-333.
30. Klinkenberg, L.J. (1941), "The Permeability of Porous Media to Liquid and Gases", American Petroleum Institute, Drilling and Production Practice, 200.
31. Lambe, T.W. (1954), "The Permeability of Fine Grained Soils", Permeability of Soils, ASTM STP 163, American Society of Testing Materials, pp. 56-67.
32. Lambe, T.W., (1958), "The Engineering Behavior of Copacted Clay", Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 84, SM2, pp. 1655 1-35.
33. Lambe, T.W. (1958), "The Structure of Compacted Clay", Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 84, SM2, pp. 1654 1-34.
34. Low, P.F. (1961), "Physical Chemistry of Clay-Water Interaction", Advances in Agronomy, Vol. 13, pp. 269-327, Academic, New York.

35. Low, P.F. (1979), "Nature and Properties of Water in Montmorillonite-Water Systems", Soil Science Society of America, Proceedings, Vol. 49, pp. 651-658.
36. Macey, H.H. (1942), "Clay-Water Relationship and the Internal Mechanisms of Drying", Trans. Br. Ceram. Soc., 41, pp. 73-121.
37. Marshall, T.J. (1958), "A Relation Between Permeability and Size Distribution of Pores", Journal of Soil Science, Vol. 9, No. 1, pp. 1-8.
38. Martin, R.T. (1962), "Adsorbed Water on Clay: A Review", Clays and Clay Minerals, Vol. 9, pp. 28-70.
39. Mesri, G. and Olson, R.E. (1971), "Mechanisms Controlling the Permeability of Clays", Clays and Clay Minerals, Vol. 19, pp. 151-158.
40. Michaels, A.S. and Lin, C.S. (1954), "Permeability of Kaolinite", Industrial and Engineering Chemistry, Vol. 46, No. 6, pp. 1239-1246.
41. Michaels, A.S. and Lin, C.S. (1955), "Effects of Counterelectro-osmosis and Sodium Ion Exchange on Permeability of Kaolinite", Industrial and Engineering Chemistry, Vol. 47, No. 6, pp. 1249-1253.
42. Miller, R.J. and Low, P.F. (1963), "Threshold Gradient for Water Flow in Clay Systems", Soil Science Society of America Proceeding, Vol. 27, pp. 605-609.
43. Miller, R.J., Overman, A.R. and Paverly, J.H. (1969), "The absence of Threshold Gradients in Clay Water Systems", Soil Science Society of America Proceedings, Vol. 33, No. 2, pp. 183-187.
44. Millington, R.J. and Quirk, J.P. (1959), "Permeability of Porous Media", Nature, Vol. 183, February, pp. 387-388.
45. Mitchell, J.K. (1976), Fundamentals of Soil Behavior, John Wiley and Sons, New York, 422 pp.
46. Mitchell, J.K. and Younger, J.S. (1967), "Abnormalities in Hydraulic Flow Through Fine-Grained Soils", Permeability and Capillarity of Soils, ASTM STP 417, pp. 106-139.
47. Muskat, M. (1937), "The Flow of Homogeneous Fluids Through Porous Media", McGraw Hill, New York.

48. Olsen, H.W. (1962), "Hydraulic Flow Through Saturated Clays", Clays and Clay Minerals, 11, pp. 131-161.
49. Olsen, H.W. (1965), "Deviations From Darcy's Law in Saturated Clays", Soil Science Society of America Proceedings, Vol. 29, pp. 135-140.
50. Olsen, H. W. (1966), "Darcy's Law in Saturated Kaolinite", Water Resources Research, Vol. 2, pp. 287-295.
51. Purcell, W.R. (1949), "Capillary Pressures Their Measurement Using Mercury and the Calculation of Permeability Therefrom", Petroleum Transactions, AIME, Vol. 186, pp. 39-48.
52. Reed, M.A. (1977), "Frost Heaving Rate of Silty Soils as a Function of Pore Size Distribution", MSCE Thesis, Purdue University, West Lafayette, Indiana, August, 116 pp.
53. Reed, M.A., Lovell, C.W., Altschaeffl, A.G. and Wood, L.E. (1980), "Reply to Discussion on 'Frost Heaving Rate Predicted from Pore Size Distribution'", Canadian Geotechnical Journal, Vol. 17, No. 4, pp. 639-640.
54. Reeve, R.C. (1953), "A Method for Determining the Stability of Soil Structure Based Upon Air and Water Permeability Measurements", Soil Science Society of America Proceedings, Vol. 17, pp. 324-329.
55. Ritter, H.L. and Drake, L.C. (1945), "Pore Size Distribution in Porous Materials", Industrial and Engineering Chemistry, Analytical Edition, American Chemical Society, Vol. 17, pp. 782-786.
56. Rootare, H.M. (1968), "A Short Literature Review of Mercury Porosimetry as a Method of Measuring Pore Size Distribution in Porous Materials, and a Discussion of Possible Sources of Errors in This Method", Aminco Lab News, Vol. 24, No. 3, pp. 4A-4H.
57. Russel, D.A. and Swartzendruber, D. (1971), "Flux-Gradient Relationships for Saturated Flow of Water Through Mixtures of Sand, Silt, and Clay", Soil Science Society of America Proceedings, Vol. 35, pp. 21-26.
58. Scheidegger, A.E. (1974), The Physics of Flow Through Porous Media, 3rd Edition, University of Toronto Press, 351 pp.
59. Schmid, W.E. (1957), "The Permeability of Soils and the Concept of a Stationary Boundary Layer", Proceedings,

- American Society of Testing Materials, Vol. 57, pp. 1195-1218.
60. Seed, H.B. and Chan, C.M. (1959), "Structure and Strength Characteristic of Compacted Clays", Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 85, SM5, pp. 87-128.
 61. Serracin, B. (1980), "Air Permeability for Compacted Clays", Internal Report No. 63, Ground Engineering, Purdue University, West Lafayette, Indiana, May, 19 pp.
 62. Silveira, A. (1965), "An Analysis of the Problem of Washing Through in Protective Filters", Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering, Montreal, Vol. II, pp. 551-555.
 63. Sridharan, A., Altschaeffl, A.G. and Diamond, S. (1971), "Pore Size Distribution Studies", Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 97, SM5, pp. 771-787.
 64. Sullival, R.R. and Hertel, K.L. (1940), "The Flow of Air Through Porous Media", Journal of Applied Physics, Vol. 11, pp. 761-765.
 65. Taylor, D.W. (1948), Fundamentals of Soil Mechanics, J.Wiley and Sons, Inc., New York, pp. 700.
 66. Tovey, N.K. and Yan, W.K. (1973), "The Preparation of Soils and other Geological Materials for SEM", Proceedings of the International Symposium on Soil Structure, Gothenburg, Sweden, pp. 59-67.
 67. Von Englehardt, W. and Tunn, W.L.M. (1955), "The Flow of Fluids Through Sand Stones", Illinois State Geological Survey Circular 194.
 68. Washburn, E.W. (1921), "Note on a Method of Determining the Distribution of Pore Sizes in a Porous Material", Proceedings, National Academy of Sciences, Vol. 7, pp. 115-116.
 69. White, D. (1980), "The Fabric of a Medium Plastic Clay Compacted in the Laboratory and in the Field", MSCE Thesis, Purdue University, West Lafayette, Indiana, pp. 95.
 70. Winslow, D.N. (1969), "The Pore Size Distribution of Portland Cement", MSCE Thesis, Purdue University, Indiana, January, 102 pp.

71. Winslow, D.N. and Diamond, S. (1970), "A Mercury Porosimeter Study of the Evaluation of Porosity in Portland Cement", Journal of Materials, ASTM, Vol. 5, No. 3, pp. 564-585.
72. Yong, R.N. and Sheeran, D.E. (1973), "Fabric Unit Interaction and Soil Behavior", Proceedings, International Symposium on Soil Structure, Swedish Geotechnical Society, Gothenburg, pp. 176-183.
73. Yong, R.N. and Warkentin, B.P. (1975), Soil Properties and Behavior, Elsevier, New York, 449 pp.
74. Zimmie, T.F. and Almaleh, L.J. (1976), "Shrinkage of Soil Specimens During Preparation For Porosimetry Tests", Soil Specimen Preparation for Laboratory Testing, ASTM STP 599, pp. 202-215.

APPENDICES

APPENDIX A

Pore Size Distribution Curves

Figure 42 Pore Size Distribution Curves for Sample S9HW

Figure 43 Pore Size Distribution Curves for Sample S9MW

Figure 44 Pore Size Distribution Curves for Sample S7H0

Figure 45 Pore Size Distribution Curves for Sample S7M0

Figure 46 Pore Size Distribution Curves for Sample S7LO

Figure 47 Pore Size Distribution Curves for Sample S5MD

Figure 48 Pore Size Distribution Curves for Sample S5M0

Figure 49 Pore Size Distribution Curves for Sample S5LD

Figure 50 Pore Size Distribution Curves for Sample S5LO

Figure 51 Pore Size Distribution Curves for Sample Alvin-B

Figure 52 Pore Size Distribution Curves for Sample Ava-B

Figure 53 Pore Size Distribution Curves for Sample Bryce-A

Figure 54 Pore Size Distribution Curves for Sample Cisne-B

Figure 55 Pore Size Distribution Curves for Sample Herrick-A

Figure 56 Pore Size Distribution Curves for Sample Hosmer-A

Figure 57 Pore Size Distribution Curves for Sample Hosmer-B

Figure 58 Pore Size Distribution Curves for Sample Richview-B

Figure 59 Pore Size Distribution Curves for Sample Sable-B

Figure 60 Pore Size Distribution Curves for Sample Stoy-A

APPENDIX - B

Derivation of Permeameter Equation (from Dolch, 1956)

Figure 61 shows the schematic diagram of the air permeability apparatus used in this study.

The mass of air, m , on the low pressure side of the sample at any time during the decay process is

$$m = P_h(V_h - h \frac{A_t}{2})\rho_1 \quad (B1)$$

where P_h - Pressure on the low pressure side of the sample

V_h - Volume of the apparatus on the low pressure side
of the sample when the differential manometer is
at equilibrium

h - Height difference on the differential manometer

A_t - Internal cross sectional area of the differential
manometer tube

ρ_1 - Density of the air at unit pressure, i.e. $\rho_1 = m/RT$

where m = Molecular weight

R - Gas constant

T - Absolute temperature

The time rate of change of m is the mass flow rate assuming steady state conditions. These are not, of course, steady state conditions. Kamack (1954), however, stated for a similar set of circumstances "...a negligible error is involved in assuming that the air instantly

Figure 61 Schematic Diagram of the Air Permeability Apparatus

adjusts itself to the equilibrium flow rate corresponding to the pressure drop. This situation is usually referred to as a quasi-stationary state". If, then, steady state conditions are assumed and equation (B1) is differentiated with respect to t , the result is

$$\frac{dm}{dt} = \rho_l \left[\frac{dP_h}{dt} - \frac{A_t}{2} \left(\frac{hdP_h}{dt} + P_h \frac{dh}{dt} \right) \right] \quad (B2)$$

The approach velocity at mean pressure, u_a , is given by

$$u_a = \frac{1}{A_s \rho_l P_m} \left(\frac{dm}{dt} \right) \quad (B3)$$

where A_s = Approach area of the sample

P_m = Mean pressure across the sample

From B2 and B3

$$u_a = \frac{1}{AP_m} \left[V_h \frac{dP_h}{dt} - \frac{A_t}{2} \left(\frac{hdP_h}{dt} + P_h \frac{dh}{dt} \right) \right] \quad (B4)$$

The physical permeability, K , for the case of gaseous flow is defined by Muskat, via Darcy's law, as

$$u_a = \frac{K \Delta P}{\mu L} \quad (B5)$$

where ΔP = head loss across the sample in pressure units

μ = viscosity of the gas

L = macro length of the sample

substituting B4 in B5 yields,

$$K = \frac{\mu L}{\Delta P A_s P_m} \left[\left(V_h - \frac{h A_t}{2} \right) \left(\frac{dP_h}{dt} \right) - P_h \frac{A_t}{2} \frac{dh}{dt} \right] \quad (B6)$$

In SI units,

$$\mu = \text{KN.s/m}^2$$

$$\Delta P, P_h, P_m = \text{KN/m}^2$$

$$V_h = \text{m}^3$$

$$L, h = m^2$$

$$A_s, A_t = m^2$$

$$t = \text{sec}$$

$$K = m^2$$

APPENDIX C

Pore Size Distribution Computer Programs

```

C      PROGRAM PORE (INPUT,OUTPUT,TAPES=INPUT,TAPE6=OUTPUT,PLOT)
C
C      THIS PROGRAM CALCULATES AND TABULATES PORE SIZE DISTRIBUTION
C      PARAMETERS, ALONG WITH PLOTTING PORE DIAMETER VERSUS CUMULATIVE
C      POROSITY AND POROSITY DENSITY FUNCTION. THIS PROGRAM WAS
C      ORIGINALLY WRITTEN BY REED(1977) AND MODIFIED BY PRAPAHARAN(1977)
C
C      INTEGER TITLE(3)
C      REAL CMSP(50),CUPORD(50)
C      REAL S(50),P(50),PS(50),D(50),SP(50),CUSP(50)
C
C      A=0.0
C      READ,NSET
C      CALL PLOTS
C      DO 22 L=1,NSET
C      NL=0
C      B=0.0
C      READ,NDATA
C
C      DO 21 J=1,NDATA
C      READ(5,1) TITLE
1      FORMAT(3A10)
C      WRITE(6,2) TITLE
2      FORMAT(1H1//5X,#SAMPLE CODE: #,3A10//)
C
C      THE PURPOSE OF THIS DO LOOP IS TO BE ABLE TO CALCULATE RESULTS FOR
C      MORE THAN ONE SET OF DATA IN A SINGLE RUN. NDATA IS THE NUMBER
C      OF SETS OF DATA TO BE CALCULATED. NDATA IS AN INTEGER VALUE, AND
C      IS THE FIRST DATA CARD FOR THE SET OF DATA.
C      DETERMINATION OF PORE SIZE DISTRIBUTION
C
C
C      READ,WS,DS,DM,UP,WSP,WSPM,PE,PF,SR
C      PRINT,WS,DS,DM,UP,WSP,WSPM,PE,PF,SR
C
C      WS=WEIGHT OF SAMPLE, DS=SPECIFIC GRAVITY OF SOLIDS, DM=DENSITY OF
C      MERCURY, UP=VOLUME OF PENETROMETER, WSP=WEIGHT OF SAMPLE AND PEN-
C      ETROMETER, WSPM=WEIGHT OF SAMPLE , PENETROMETER AND MERCURY,
C      PE =EVACUATING PRESSURE, PF=FILLING PRESSURE,IN MM OF MERCURY,
C      SR =STEM READING AT FILLING PRESSURE. THE ABOVE VALUES ARE ALL ON
C      THE SAME DATA CARD
C
C      US=WS/DS
C      WM=WSPM - WSP
C      UM=WM/DM
C      USA=UP-UM*(1.+PE/PF)-SR
C      UVO=USA-US
C      VOIDR=UVO/US
C      POROS=UVO/USA
C      PU=PE*UM
C      UAI=PU/PF
C
C      WRITE(6,3) US,UVO,VOIDR,POROS
3      FORMAT(///T10,#VOLUME OF SOLIDS =#,F8.6//
1          T11,#VOLUME OF VOIDS =#,F8.6//
2          T16,#VOID RATIO =#,F8.6//
3          T18,#POROSITY =#,F8.6//)

```

```

C      READ,N,M,SI
C
C      N=INTEGER VALUE FOR THE NUMBER OF LOW PRESSURE READINGS MADE, NOT
C      COUNTING THE FILLING PRESSURE READING.  M=INTEGER VALUE FOR THE
C      NUMBER OF HIGH PRESSURE READINGS MADE, NOT COUNTING THE INITIAL
C      POROSIMETER READING.  SI=INTRUSION READING AT INITIATION PRESSURE
C      IN ML.  THE THREE VALUES ARE ALL ON ONE DATA CARD.
C
C      LOW PRESSURE CALCULATIONS
C
C      WRITE(6,4)
4      FORMAT(1H1//,37X, #LOW PRESSURE CALCULATIONS#//)
C      WRITE(6,5)
5      FORMAT(//T5, #MM OF HG#, T20, #PRESSURE#, T35, #VOLUME OF#, T50, #STEM#,
1      T65, #INTRUSION#, T80, #INCREMENTAL#, T95, #CUMULATIVE#, T110,
2      #DIAMETER#/T38, #AIR#,
3      T49, #READING#, T81, #POROSITY#, T96, #POROSITY#, T110, #(MICRON)#//)
C
C      CUSP(1) = 0.
C
C      DO 7   I=2,N+1
C          READ,PS(I),S(I)
C
C      P(I) AND S(I) ARE THE PRESSURE AND INTRUSION VALUES FOR EACH
C      READING, P(I) IS GIVEN IN MM OF MERCURY FOR THE LOW PRESSURE
C      INTRUSION AND PSI FOR THE HIGH PRESSURE.  S(I) IS IN ML.  THE TWO
C      VALUES ARE TYPED ON ONE DATA CARD, WITH A CARD FOR EACH READING.
C
C      P(I)=PS(I)*0.01934
C      UA=PU/PS(I)
C      CUA=UAI-UA
C      CSR=S(I)-SR
C      SN=CSR-CUA
C      IF (SN.LT.0.) SN = 0.0
C      SP(I) = SN/UA
C      CUSP(I) = CUSP(I-1) +SP(I)
C      CUPORO(I) = CUSP(I)/POROS
C      D(I)=[(-4.)*484.*COS(2.5656)*.145]/P(I)
C      IF (CUPORO(I).LE.0.10) DM1 = D(I)
C
C      P(I)=INTRUSION PRESSURE IN MM OF MERCURY, PS=INTRUSION PRESSURE IN
C      PSI, UA=VOLUME OF AIR IN ML, S(I)=STEM READING, SN=CORRECTED
C      INTRUSION FOR EACH INCREMENT IN ML, SG=CORRECTED INTRUSION /GRAM
C      FOR EACH INCREMENT, CU(I)=CUMULATIVE CORRECTED INTRUSION/GRAM,
C      SP(I)=INCREMENTAL POROSITY, CUSP(I)=CUMULATIVE POROSITY,
C      D(I)=LIMITING PORE SIZE DIAMETER
C
C      WRITE(6,6) PS(I),P(I),UA,S(I),SN,SP(I),CUSP(I),D(I)
6      FORMAT(4X,F7.1,T21,F5.2,T36,F6.5,T50,F5.4,T67,F6.5,T83,F6.5,
1      T97,F6.5,T111,F6.2)
C      UAI=UA
7      SR=S(I)
C
C      HIGH PRESSURE CALCULATIONS
C
C      WRITE(6,8)
8      FORMAT(//,36X, #HIGH PRESSURE CALCULATIONS#//)

```

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      WRITE(6,9)
9    FORMAT(/,T5,#PRESSURE#,T20,#STEM#,T35,#MER. COMP.#,T50,#INTRUSION#,
1    T65,#INCREMENTAL#,T80,#CUMULATIVE#,T95,#DIAMETER#/T7,#(PSI)#,T19,
2    #READING#,T35,#CORRECTION#,T67,#POROSITY#,T82,#POROSITY#,T95,
3    #(MICRON)#/)
C
      HCI=11.*.0011*UM/15000.
C
      DO 11 I=N+2,M+N+1
      READ,P(I),S(I)
      P(I)=P(I)+11.
C
C    HC IS CORRECTION FOR COMPRESSION OF MERCURY
C
      HC=P(I)*.0011*UM/15000.
      CHC=HC-HCI
      CSR=S(I)-SI
      SN=CSR-CHC
      SP(I) = SN/USA
      CUSP(I) = CUSP(I-1) + SP(I)
      CUPORO(I) = CUSP(I)/POROS
C
C    D(I) PORE DIAMETER CALCULATIONS BASED ON A SURFACE TENSION VALUE
C    OF 484 DYNES / CM AND A CONTACT ANGLE OF 147 DEGREES.
C
      D(I)=[(-4.)*484.*COS(2.5656)*.145]/P(I)
      IF (CUPORO(I).LE.0.10) DM1 = D(I)
C
C    P(I)=INTRUSION PRESSURE IN PSI, S(I)=STEM READING, HC=MERCURY
C    CORRECTION, CHC=CHANGE IN MERCURY CORRECTION IN ML, SN=CORRECTED
C    INTRUSION IN ML, SGH=CORRECTED INTRUSION /GRAM, CU(I)=CUMULATIVE
C    CORRECTED INTRUSION/GRAM, SP(I)=INCREMENTAL POROSITY, CUSP(I)=
C    CUMULATIVE POROSITY)
C
      WRITE(6,10) P(I),S(I),CHC,SN,SP(I),CUSP(I),D(I)
10    FORMAT(4X,F7.1,T20,F5.4,T36,F6.5,T51,F6.5,T68,F6.5,T83,F6.5,
1    T96,F6.3)
C
      HCI=HC
11    SI=S(I)
C
      D(1)=-4.*484.*COS(2.5656)*0.145/(0.01934*PF)
C
      DO 12 I = 2,N+M+1
      CMSP(I) = SP(I)
12    CONTINUE
C
C    BELOW - CALCULATION OF MEAN PORE DIAMETER AND SECOND MOMENT ABOUT
C    THE ORIGIN. 10 PERCENT OF THE PORE VOLUME ON THE LARGER PORE
C    SIDE IS IGNORED
C
      SUM1 = 0.0
      SUM2 = 0.0
      DO 13 I=2,N+M+1
      DM = SQRT(D(I)*D(I-1))
      IF(DM.GT.DM1) DM=0.0
      SUM1 = SUM1 + SP(I)*DM

```

```

13  SUM2 = SUM2 + SP(I)*DM**2
    DMEA1= SUM1/POROS
    DMEA2= SUM2/POROS
    WRITE (6,14)
14  FORMAT(1H1,S(/),10X,THE STATISTICAL MEASURES BELOW NEGLECT PORES=
A,/,10X,WHEN THE CUMULATIVE POROSITY IS LESS THAN 10 PERCENT////)
    WRITE(6,15) DMEA1,DMEA2,SUM2
15  FORMAT(/T10,ADJUSTED MEAN PORE SIZE=,E10.4//
    IT10,ADJUSTED SECOND MOMENT ABOUT THE ORIGIN=,E10.4//
    2T10,CAPILLARY PARAMETER (IN MICRON**2) = ,E10.4)
C
C  BELOW - CALCULATION OF MARSHALL MODEL PORE DIAMETER
    SIGMA=0.0
    DO 17 K=2,N+M+1
        DM=D(K)
        IF (D(K).GT.DM1) CMSP(K) = 0.0
    DO 16 I=2,N+M+1
        IF(D(I).LT.D(K)) DM=D(I)
        IF(DM.GT.DM1) DM=0.0
        IF(D(I).GT.DM1) CMSP(I)=0.0
        SIGMA=SIGMA+CMSP(I)*CMSP(K)*DM**2
16  CONTINUE
17  CONTINUE
    WRITE(6,18) SIGMA
18  FORMAT(/T10,MARSHALL PORE PARAMETER (IN MICRON**2) =,E10.4/)
C
    WRITE(6,19) DM1
19  FORMAT(///9X,CUT OFF DIAMETER =,F7.2//)
C
    DO 20 I=2,N+M+1
20  D(I)=ALOG10(D(I))
C  THE PURPOSE OF THIS DO LOOP IS TO CONVERT THE PORE SIZE DIAMETER
C  TO THE LOG OF THE DIAMETER
C
    CALL PLOT(0,0.3,-3)
    CALL JPLOT2(CUSP,D,M,N,A,NL,B,POROS,J,TITLE)
    CALL PLOT(0,-0.3,-3)
C
    CALL PLOT(0,1.2,-3)
    CALL JPLOT1(D,SP,M,N,A,B,PF,NL,J,TITLE,POROS)
    CALL PLOT(0,-1.2,-3)
C
    NL=NL+1
    B=B+0.33
21  CONTINUE
    A=A+10.0
22  CONTINUE
    CALL PLOT(0,0,0.0,999)
    STOP
    END
C
C  *****
C
    SUBROUTINE JPLOT1(D,SP,M,N,A,B,PF,NL,J,TITLE,POROS)
    DIMENSION SP(50),D(50),D1(50)
    INTEGER TITLE(3)
    CALL FACTOR (1.0)
    IF(J.GT.1) GO TO 7

```

```

      CALL SYMBOL (A+1.85,.5,.7/6.,33)LIMITING PORE DIAMETER IN MICRONS,
10.0,33)
      CALL SYMBOL(A+1.,0.75,0.7/6.,
F50H.01      0.1      1.0      10.0      100.0      1000.0,0.0,50)
C   THE ABOVE PLOTS AND LABELS THE X AXIS
      DO 1 I=2,5
      CI=I
      CALL SYMBOL (A+CI,1.0,0.1,13,0.0,-1)
1   CONTINUE
C   THE ABOVE PLACES TICK MARKS ALONG THE X AXIS
      CALL SYMBOL (A+0.5,1.15,.7/6.,29)POROSITY DENSITY FUNCTION (/),
1   90.0,29)
      CALL SYMBOL (A+0.605,1.0,.7/6.,1H0,0.0,1)
      CALL SYMBOL (A+0.605,2.0,.7/6.,2H50,0.0,2)
      CALL SYMBOL (A+0.605,3.0,.7/6.,3H100,0.0,3)
      CALL SYMBOL (A+0.605,3.9,.7/6.,3H150,0.0,3)
C   THE ABOVE PLOTS AND LABELS THE Y AXIS
      DO 2 I=1,4
      CI=I
      CALL SYMBOL (A+1.0,CI,0.1,15,0.0,-1)
2   CONTINUE
C   THE ABOVE PLACES TICK MARKS ALONG THE Y AXIS
      CALL SYMBOL (A+4.40,3.80,.085,SH)LEGEND,0.0,6)
C   THE ABOVE WRITES LEGEND ON THE PLOT
      CALL PLOT (A+1.0,4.0,3)
      CALL PLOT (A+6.0,4.0,2)
      CALL PLOT (A+6.0,2.5,2)
      CALL PLOT (A+4.0,3.0,3)
      CALL PLOT (A+1.0,3.0,2)
      CALL PLOT (A+1.0,2.0,3)
      CALL PLOT (A+6.0,2.0,2)
      CALL PLOT (A+6.0,1.0,3)
      CALL PLOT (A+1.0,1.0,2)
      CALL PLOT (A+1.0,4.0,2)
      CALL PLOT (A+2.0,4.0,3)
      CALL PLOT (A+2.0,1.0,2)
      CALL PLOT (A+3.0,1.0,3)
      CALL PLOT (A+3.0,4.0,2)
      CALL PLOT (A+4.0,4.0,3)
      CALL PLOT (A+4.0,1.0,2)
      CALL PLOT (A+5.0,1.0,2)
      CALL PLOT (A+5.0,2.5,2)
      CALL PLOT (A+6.0,2.5,3)
      CALL PLOT (A+6.0,1.0,2)
      CALL PLOT (A+1.0,1.0,2)
      DO 4 IOU=1,5
      CIOU=IOU
      DO 3 IO=2,9
      CIOA=IO
      CIO=ALOG10(CIOA)
      CALL SYMBOL (A+CIOU+CIO,1.0,.05,13,0.0,-1)
3   CONTINUE
4   CONTINUE
      CALL PLOT (A+1.0,1.0,3)
      DO 6 IO=1,3
      CIO=IO
      DO 5 IOU=1,4
      CIOU=IOU

```



```

      CIOU=CIOU/5.
      CALL SYMBOL (A+1.0,CIO+CIOU,.05,15,0.0,-1)
5      CONTINUE
6      CONTINUE
7      CONTINUE
      CALL PLOT (A+1.0,4.0,3)
      D(1)=ALOG10(-4.*484.*COS(2.5656)*0.145/(0.01934*PF))
      DO 8 I=2,N+M+1
      D(I-1)=D(I-1)-D(I)
      D(I-1)=(D(I)+D(I-1))/2
8      SP(I-1)=SP(I)/POROS/D1(I-1)
      D(M+N+1)=-3.0-A
      D(M+N+2)=1.0
      SP(M+N+1)=-0.5
      SP(M+N+2)=0.5
      CALL SYMBOL (A+4.10,3.59-B,.07,NL,0.0,-1)
      CALL SYMBOL (A+4.30,3.55-B,.080,11HSAMPLE CODE,0.0,11)
      CALL SYMBOL (A+5.20,3.55-B,.080,TITLE,0.0,30)

C
C      THE ABOVE LISTS THE WATER CONTENT AND PERMEABILITY FOR THE PORE
C      SIZE CURVE
C
      CALL LINE(D,SP,M+N,1,1,NL)
C
C      THE ABOVE PLOTS THE ACTUAL PORE SIZE CURVE
C
C      B IS FOR THE PLACEMENT OF THE PERMEABILITY AND WATER CONTENT
C      VALUES.
      RETURN
      END

C
C      *****
C
      SUBROUTINE JPLT2(CUSP,D,M,N,A,NL,B,POROS,J,TITLE)
      INTEGER TITLE(3)
      REAL D(50),CUSP(50)
      CALL FACTOR (1.0)
      IF(J.GT.1) GO TO 3
      CALL SYMBOL(A+1.85,5.5,.7/6.,.33HLIMITING PORE DIAMETER IN MICRONS,
      GO,0,33)
      CALL SYMBOL(A+1.,5.75,0.7/6.,
      F50H.01      0.1      1.0      10.0      100.0      1000.0,0.50)
C      THE ABOVE PLOTS AND LABELS THE X AXIS
      CALL SYMBOL (A+2.0,6.0,0.1,3,0.0,-1)
      CALL SYMBOL (A+3.0,6.0,0.1,3,0.0,-1)
      CALL SYMBOL (A+4.0,6.0,0.1,3,0.0,-1)
      CALL SYMBOL (A+5.0,6.0,0.1,3,0.0,-1)
C      THE ABOVE PLACES TICK MARKS ALONG THE X AXIS
      CALL SYMBOL (A+0.5,6.4,.7/6.,.23HCUMULATIVE POROSITY (/),90.0,23)
      CALL SYMBOL (A+0.605,6.0,.7/6.0,1H0,0.0,1)
      CALL SYMBOL (A+0.605,7.0,.7/6.0,2H50,0.0,2)
      CALL SYMBOL (A+0.605,8.0,.7/6.0,3H100,0.0,3)
      CALL SYMBOL (A+0.605,8.9,.7/6.0,3H150,0.0,3)
C      THE ABOVE PLOTS AND LABELS THE Y AXIS
      CALL SYMBOL (A+1.0,7.0,0.1,3,0.0,-1)
      CALL SYMBOL (A+1.0,8.0,0.1,3,0.0,-1)
      CALL SYMBOL (A+1.0,9.0,0.1,3,0.0,-1)
C      THE ABOVE PLACES TICK MARKS ALONG THE Y AXIS

```

```

C      CALL SYMBOL (A+4.40,8.80,.085,6HLEGEND,0.0,6)
C      THE ABOVE WRITES LEGEND ON THE PLOT
      CALL PLOT (A+1.0,9.0,3)
      CALL PLOT (A+6.0,9.0,2)
      CALL PLOT (A+6.0,6.0,2)
      CALL PLOT (A+1.0,6.0,2)
      CALL PLOT (A+1.0,9.0,2)
C      THE ABOVE 5 CARDS DRAW THE OUTLINE OF THE GRAPH
C      THESE CARDS FURTHER LABEL THE GRAPH AND PROVIDE THE GRID.
      CALL PLOT(A+1.0,8.0,3)
      CALL PLOT(A+4.0,8.0,2)
      CALL PLOT(A+1.0,7.0,3)
      CALL PLOT(A+6.0,7.0,2)
      CALL PLOT(A+5.0,6.0,3)
      CALL PLOT(A+5.0,7.5,2)
      CALL PLOT(A+4.0,9.0,3)
      CALL PLOT(A+4.0,6.0,2)
      CALL PLOT(A+3.0,6.0,3)
      CALL PLOT(A+3.0,9.0,2)
      CALL PLOT(A+2.0,9.0,3)
      CALL PLOT(A+2.0,6.0,2)
      DO 2 IOU=1,5
      CIOU=IOU
      DO 1 IO=2,9
      CIOA=IO
      CIO=ALOG10(CIOA)
      CALL SYMBOL (A+CIOU+CIO,6.0,.05,3,0.0,-1)
1      CONTINUE
2      CONTINUE
3      CONTINUE
      CALL PLOT (A+1.0,6.0,3)
      DO 4 I=2,M+N+1
      D(I-1)=D(I)
4      CUSP(I-1)=CUSP(I)/POROS
      D(M+N+1)=-3.0-A
      D(M+N+2)=1.0
      CUSP(M+N+1)=-3.00
      CUSP(M+N+2)=0.5
      CALL SYMBOL (A+4.10,8.59-B,.07,NL,0.0,-1)
      CALL SYMBOL(A+4.30,8.55-B,.080,11HSAMPLE CODE,0.0,11)
      CALL SYMBOL(A+5.20,8.55-B,0.08,TITLE,0.0,30)
C
C      THE ABOVE LISTS THE WATER CONTENT AND PERMEABILITY FOR THE PORE
C      SIZE CURVE
C
      CALL LINE (D,CUSP,N+M,1,1,NL)
C
C      THE ABOVE PLOTS THE ACTUAL PORE SIZE CURVE
C      STEPS BELOW PLOT TOTAL POROSITY ON THE ORDINATE
C
C      B IS FOR THE PLACEMENT OF THE PERMEABILITY AND WATER CONTENT
C      VALUES.
      DO 5 I=1,N+M
      IA=N+M+1-I
5      D(IA+1)=D(IA)
      RETURN
      END

```

```

      PROGRAM PORE (INPUT,OUTPUT,TAPES=INPUT,TAPE6=OUTPUT,PLOT)
C
C   THIS PROGRAM PLOTS SUCTION VS WATER CONTENT GRAPHS OBTAINED
C   FROM CONVENTIONAL METHODS AND MERCURY INTRUSION TECHNIQUE
C   IN THE SAME AXES FOR THE PURPOSE OF COMPARISON
C
      INTEGER TITLE(3)
      REAL DWC(30),SUCTN(30)
      REAL PS(50),S(50),P(50),CU(50),PW1(50),PW(50),WC(50)
      A=0.0
      C=0.0
      READ,NSET
      CALL PLOTS
      CALL PLOT(2.0,1.2,-3)
      DO 13 L=1,NSET
      NL=0
      E=0.0
      READ,NDATA
      READ(S,*) W
C
C   W = SATURATED WATER CONTENT
C
      PW1(1)=0.
      WC(1)=W
C
      READ(S,*) NUMSUC
C   NUMSUC = NUMBER OF EXPERIMENTAL READINGS
C
      WRITE(6,1)
1   FORMAT(1H1,S(/),T25,=CONVENTIONAL METHOD=)
      WRITE(6,2)
2   FORMAT(///T20,=WATER CONTENT=,T40,=SUCTION=,/,T22,=(PERCENT)=,
1      T39,=(CM WATER)=///)
C
C   READ EXPERIMENTAL SUCTION AND WATER CONTENT DATA
C
      DO 4 I=1,NUMSUC
      READ(S,*) DWC(I),SUCTN(I)
      WRITE(6,3) DWC(I),SUCTN(I)
3   FORMAT(T25,F5.2,T40,F8.1)
      SUCTN(I)=1.6*ALOG10(SUCTN(I))
4   CONTINUE
C
C   DWC = WATER CONTENT
C   SUCTN = SUCTION
C
      DO 12 J=1,NDATA
      READ(S,5) TITLE
      FORMAT(3A10)
C
C   THE PURPOSE OF THIS DO LOOP IS TO BE ABLE TO CALCULATE RESULTS FOR
C   MORE THAN ONE SET OF DATA IN A SINGLE RUN. NDATA IS THE NUMBER
C   OF SETS OF DATA TO BE CALCULATED. NDATA IS AN INTEGER VALUE, AND
C   IS THE FIRST DATA CARD FOR THE SET OF DATA.
C   DETERMINATION OF PORE SIZE DISTRIBUTION
C
C
C
C

```

```

C      READ,WS,DS,DM,UP,WSP,WSPM,PE,PF,SR
C
C      WS=WEIGHT OF SAMPLE, DS=SPECIFIC GRAVITY OF SOLIDS, DM=DENSITY OF
C      MERCURY, UP=VOLUME OF PENETROMETER, WSP=WEIGHT OF SAMPLE AND PEN-
C      ETROMETER, WSPM=WEIGHT OF SAMPLE , PENETROMETER AND MERCURY,
C      PE =EVACUATING PRESSURE, PF=FILLING PRESSURE, IN MM OF MERCURY,
C      SR =STEM READING AT FILLING PRESSURE.  THE ABOVE VALUES ARE ALL ON
C      THE SAME DATA CARD
C
C      WM=WSPM - WSP
C      UM=WM/DM
C      PU=PE*UM
C      UAI=PU/PF
C
C      READ,N,M,SI
C
C      N=INTEGER VALUE FOR THE NUMBER OF LOW PRESSURE READINGS MADE, NOT
C      COUNTING THE FILLING PRESSURE READING.  M=INTEGER VALUE FOR THE
C      NUMBER OF HIGH PRESSURE READINGS MADE, NOT COUNTING THE INITIAL
C      POROSIMETER READING.  SI=INTRUSION READING AT INITIATION PRESSURE
C      IN ML.  THE THREE VALUES ARE ALL ON ONE DATA CARD.
C
C      LOW PRESSURE CALCULATIONS
C
C      CU(1) = 0.
C      DO 8 I=2,N+1
C      READ,PS(I),S(I)
C
C      P(I) AND S(I) ARE THE PRESSURE AND INTRUSION VALUES FOR EACH
C      READING, P(I) IS GIVEN IN MM OF MERCURY FOR THE LOW PRESSURE
C      INTRUSION AND PSI FOR THE HIGH PRESSURE.  S(I) IS IN ML.  THE TWO
C      VALUES ARE TYPED ON ONE DATA CARD, WITH A CARD FOR EACH READING.
C
C      P(I)=PS(I)*0.01934
C      UA=PU/PS(I)
C      CUA=UAI-UA
C      CSR=S(I)-SR
C      SN=CSR-CUA
C      IF (SN.LT.0.) GO TO 6
C      SG =SN/WS
C      GO TO 7
6      SG=0.
C      SN =0.
7      CU(I) = CU(I-1) + SG
C      WC(I)=W-CU(I)*100.
C      PW(I)=12.129811*P(I)
C
C      12.129811 IS THE CONVERSION FACTOR
C
C      PW1(I)= 1.6*ALOG10(PW(I))
C
C      P(I)=INTRUSION PRESSURE IN MM OF MERCURY, PS=INTRUSION PRESSURE IN
C      PSI, UA=VOLUME OF AIR IN ML, S(I)=STEM READING, SN=CORRECTED
C      INTRUSION FOR EACH INCREMENT IN ML, SG=CORRETED INTRUSION /GRAM
C      FOR EACH INCREMENT, CU(I)=CUMULATIVE CORRECTED INTRUSION/GRAM,
C      D(I)=LIMITING PORE SIZE DIAMETER
C
C      UAI=UA

```

```

8      SR=S(I)
C
C      HIGH PRESSURE CALCULATIONS
C
      HCI=11.*.0011*UM/15000.
      DO 9      I=N+2,M+N+1
      READ,P(I),S(I)
      P(I)=P(I)+11.
C
C      HC IS CORRECTION FOR COMPRESSION OF MERCURY
C
      HC=P(I)*.0011*UM/15000.
      CHC=HC-HCI
      CSR=S(I)-SI
      SN=CSR-CHC
      SGH=SN/WS
      CU(I)=CU(I-1)+SGH
      WC(I)=W-CU(I)*100.
      PW(I)=P(I)*12.129811
      PW1(I)= 1.6*ALOG10(PW(I))
C
C      P(I)=INTRUSION PRESSURE IN PSI, S(I)=STEM READING, HC=MERCURY
C      CORRECTION, CHC=CHANGE IN MERCURY CORRECTION IN ML, SN=CORRECTED
C      INTRUSION IN ML, SGH=CORRECTED INTRUSION /GRAM, CU(I)=CUMULATIVE
C      CORRECTED INTRUSION/GRAM
C
      HCI=HC
9      SI=S(I)
C
      WRITE(6,10)
10     FORMAT(1H1,8(/),T25,=MERCURY INTRUSION METHOD=)
      WRITE(6,2)
      DO 11 I = 2,N+M+1
          WRITE(6,3) WC(I),PW(I)
11     CONTINUE
C
      CALL JPLOT(PW1,WC,M,N,A,NL,C,J,E,TITLE,DWC,SUCTN,NUMSUC)
      NL=NL+1
      E=E+.40
12     CONTINUE
      A=A+10.0
      C=C+50.0
13     CONTINUE
      CALL PLOT(0.0,0.0,999)
      STOP
      END
C
C      *****
C
C      SUBROUTINE JPLOT(PW1,WC,M,N,A,NL,C,J,E,TITLE,DWC,SUCTN,NUMSUC)
      INTEGER TITLE(3)
      REAL MC,WC(50),PW(50),PW1(50),DWC(30),SUCTN(30)
      CALL FACTOR(0.8)
      IF(J.GT.1) GO TO 21
      CALL SYMBOL(A+3.17,0.9,.7/6.,17HWATER CONTENT ( ),0.0,17)
      CALL SYMBOL(A+1.,1.25 ,.7/6 .,
1  61H0          5          10          15          20          25          30
2      ,0.,61)

```

```

DO 14 I=2,7
CI=I
    CALL SYMBOL(A+CI,1.6 , .1,13.0. ,-1 )
14  CONTINUE
    CALL SYMBOL(A+ .5,4 . ,.7/6.,22HSUCTION (CM OF WATER),90.0,22)
    CALL SYMBOL(A+.7,1.6,.7/6.,1H1,0.,1)
    CALL SYMBOL (A+.6,2*1.6,.7/6.,2H10,0.,2)
    CALL SYMBOL(A+.6,3*1.6,.7/6.,3H100,0.,3)
    CALL SYMBOL(A+.6,4.0*1.6,.7/6.,4H1000,0.0,4)
    CALL SYMBOL(A+.5,5.0*1.6,.7/6.,5H10000,0.,5)
    CALL SYMBOL(A+.4,6.0*1.6,.7/6.,6H100000,0.0,6)
DO 15 I=1,7
CI=I
BI=1.6*CI
    CALL SYMBOL(A+1.,BI,0.1,15.0. ,-1)
15  CONTINUE
    CALL PLOT(A+1.,1.6,3)
    CALL PLOT(A+1.,6.0*1.6,2)
    CALL PLOT(A+7.,6.0*1.6,2)
    CALL PLOT(A+7.,1.6,2)
    CALL PLOT(A+1.,1.6,2)
DO 16 I=1,4
Y1=FLOAT(I)
    CALL PLOT(A+3.0+Y1,1.6,3)
    CALL PLOT(A+3.0+Y1,6.0*1.6,2)
16  CONTINUE
    CALL PLOT(A+2.0,3.0*1.6,3)
    CALL PLOT(A+2.0,6.0*1.6,2)
    CALL PLOT(A+3.0,6.0*1.6,3)
    CALL PLOT(A+3.0,3.0*1.6,2)
    CALL PLOT(A+4.0,2.0*1.6,3)
    CALL PLOT(A+7.0,2.0*1.6,2)
    CALL PLOT(A+7.0,3.0*1.6,3)
    CALL PLOT(A+1.0,3.0*1.6,2)
    CALL PLOT(A+1.0,4.0*1.6,3)
    CALL PLOT(A+7.0,4.0*1.6,2)
    CALL PLOT(A+7.0,5.0*1.6,3)
    CALL PLOT(A+1.0,5.0*1.6,2)
DO 18 IOU=1,5
CIOU=IOU
BIOU=1.6*CIOU
DO 17 IO=2,9
CIOA=IO
CIO=1.6*ALOG10(CIOA)
    CALL SYMBOL(A+1.,BIOU+CIO,0.05,15.0.,-1)
17  CONTINUE
18  CONTINUE
    CALL PLOT(A+1.,1.6,3)
DO 20 IO=1,6
CIO=IO
DO 19 IOU=1,5
CIOU=IOU
CIOU=CIOU/5.
    CALL SYMBOL(A+CIO+CIOU,1.6 ,.05,13.0. ,-1)
19  CONTINUE
20  CONTINUE
21  CONTINUE
    CALL SYMBOL(A+1.4,4.04,0.07,5.0.0,-1)

```

```

CALL SYMBOL(A+1.6,4.0,0.08,19HEXPERIMENTAL METHOD,0.0,19)
CALL SYMBOL(A+1.4,3.64-E,0.07,NL,0.0,-1)
CALL SYMBOL(A+1.6,3.6-E,0.08,11HSAMPLE CODE,0.0,11)
CALL SYMBOL(A+2.5,3.6-E,0.08,TITLE,0.0,30)

```

```

    WC(M+N-5)=-5.0-C

```

```

    WC(M+N-4)=5.0

```

```

    PW1(M+N-5)=-1.6

```

```

    PW1(M+N-4)=1.0

```

C

```

    DWC(NUMSUC+1)=-5.0-C

```

```

    DWC(NUMSUC+2)=5.0

```

```

    SUCTN(NUMSUC+1)=-1.6

```

```

    SUCTN(NUMSUC+2)=1.0

```

```

CALL LINE(WC,PW1,M+N-6,1,-1,NL)

```

```

CALL LINE(DWC,SUCTN,NUMSUC,1,-1,5)

```

```

RETURN

```

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END

```

APPENDIX D

Purdue University Negative Numbers for Photographs

Figure	Negative Number
3	75529-24
4	75529-34
5	75529-25
6	75529-28
7	75609-14
8	82436-11
9	82436-5
10	82436-2

COVER DESIGN BY ALDO GIORGINI